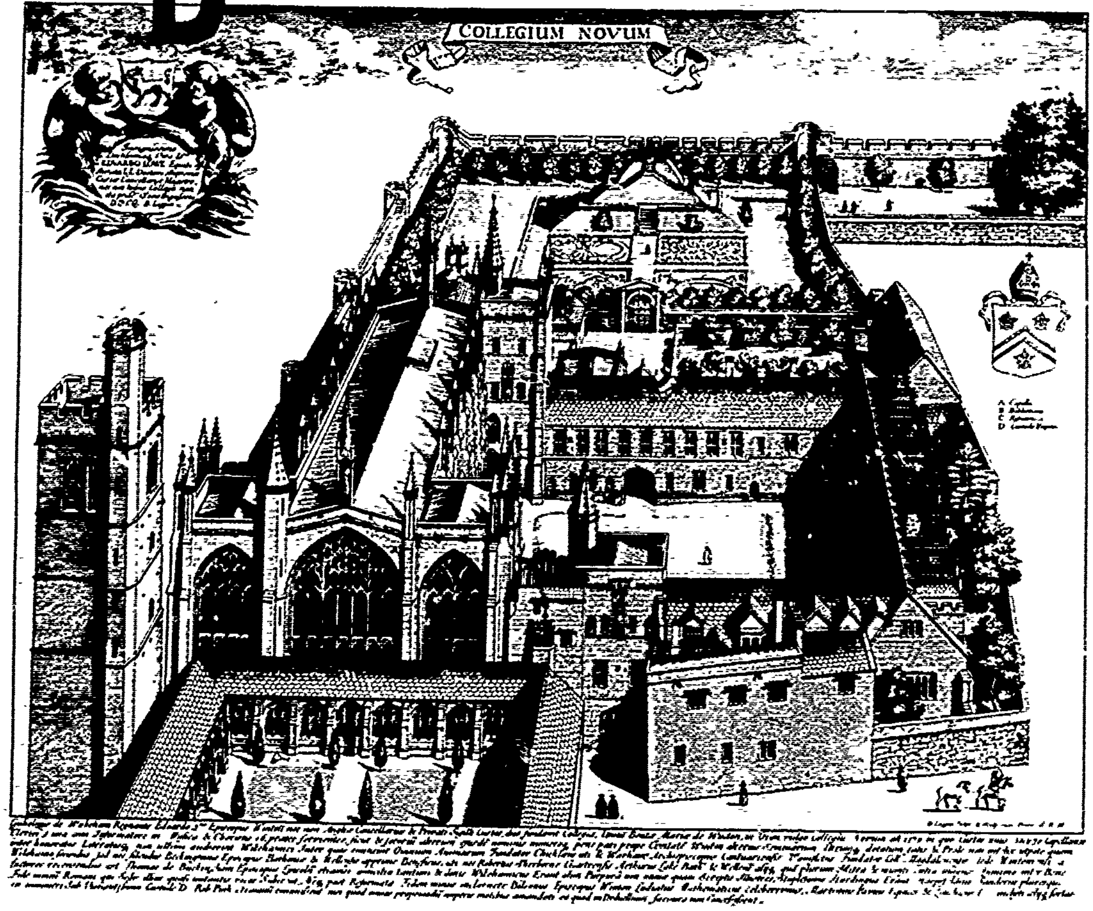
INTERNATIONAL CONFERENCE ON

The Physics of Highly Ionised Atoms

INCORPORATING THE
SEVENTH INTERNATIONAL CONFERENCE ON
BEAM FOIL SPECTROSCOPY



UNIVERSITY OF OXFORD, ENGLAND
2–5 JULY 1984

Programme and Abstracts

INTERNATIONAL CONFERENCE ON

The Physics of Highly Ionised Atoms

INCORPORATING THE
SEVENTH INTERNATIONAL CONFERENCE ON
BEAM FOIL SPECTROSCOPY

UNIVERSITY OF OXFORD, ENGLAND

2–5 JULY 1984

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This handbook contains summaries submitted by the authors for the convenience of participants in the meeting. It is not a formal publication, and the summaries should not be quoted in the literature without the prior permission of the authors. The Conference Proceedings will be published as a single volume in Nuclear Instruments and Methods B (North Holland).

The Conference is organized under the auspices of the Atomic and Molecular Sub-committee of the Institute of Physics. It is approved by IUPAP and supported by the Royal Society. We are grateful to the USAF European Office of Aerospace Research and Development and the United States Army Research, Development and Standardization Group (UK) for their support.

We would like to express our appreciation also of the support given to the Conference by the firms taking part in the Trade Exhibition (10 am - 5 pm, Wednesday 4 July in New College):

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72 - 104	Poster Session B
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INTERNATIONAL CONFERENCE ON THE PHYSICS OF HIGHLY IONISED ATOMS

New College, Oxford

1 July Sunday	*2 July Monday*	*3 July Tuesday*	*4 July Wednesday*	*5 July Thursday*
	Opening remarks 0900		Trade Show (1000–1700)	
Registration from 1600–2200	*Session I 0915–1230	*Session IV 0900–1230	*Session V 0900–1245	*Session VI 0900–1230
Buffet dinner available 1830–2030	Collision Processes involving Highly Stripped Ions	Beam Foil Spectroscopy and Surface Interactions	Spectroscopy of Highly Ionised Atoms in Laboratory and Astrophysical Sources	Novel Aspects of Highly Ionised Atoms
		LUNCH BREAK		
	*Session II 1415–1600	Poster Session A 1400–1700	Poster Session B 1400–1700	VISITS TO LABS 1400–1600
	Fundamental Problems in in Atomic Structure			JET-Culham Labs. or Rutherford & Appleton Lab.
	*Session III 1630–1740	1800 Discussion meeting		
	Novel Sources of Highly Stripped Ions			
		CONFERENCE DINNER	Visit to Royal Shakespeare Theatre Stratford upon Avon	Boat trip along the Thames

*Gulbenkian Lecture Theatre, St. Cross Building

PROGRAMME AND INDEX

		Abstract No
MONDAY 2 July, 1984		
9.00	Opening remarks	
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09.50	"Dielectronic Satellite Spectra of Multicharged Ions". V I Safronova	2
10.25	COFFEE	
10.50	"Electron Capture Processes in Low Energy Multicharged Ion-Atom Collisions" M Barat	3
11.25	"Charge-Exchange Involving Highly Stripped Ions, n, ℓ, m Distribution of Final States". A Chetioui and A Salin	4
11.45	"Review of Radiative Decay of Low Energy Charge Transfer Experiments at the AGRIPPA Facility" S Bliman, J J Bonnet, A Bordenave-Montesquieu, J Desesquelles, M Druetta, D Hitz	5
12.05	"Subshell Selective Electron Capture Cross Sections for Collisions between Highly Charged Low Z Ions and H(1s)" F J de Heer, D Dykkamp, A G Drentje	6
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15.25	"Relativistic Atomic Structure Calculations for Highly Ionised Atoms" I P Grant	9
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10.40	"Laser Resonance Measurement in Highly Ionised Atoms". E G Myers	19
11.15	"Spectroscopy of Megavolt Energy Ionised Atoms in Laser-produced Plasmas". Yu A Mikhailov	20
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ORAL CONTRIBUTIONS

ABSTRACTS 1 - 27

RECENT DEVELOPMENTS IN THE APPLICATION OF ATOMIC COLLISIONS TO FUSION RESEARCH

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Atomic collisions play a role in heating, diagnosing, and cooling plasma physics experiments. A brief survey of these issues will be presented. This will be followed by a description of several recent developments. One of the most successful methods for plasma heating has been the injection of high energy neutral hydrogen beams into the plasma. The fast neutral hydrogen atoms are "ionized" by electron and ion impact collisions and charge exchange. The fast ions are then confined by the magnetic field and slow down by binary coulomb collisions, thus heating the background plasma. Recent calculations have indicated that multiple collisions of the fast neutral atoms with the plasma increase the "stopping" cross section by as much as 50-100%. Several new diagnostic techniques based on the measurement of radiation produced from excited ions produced by the charge transfer of neutral hydrogen and ions have been developed. These diagnostics allow the measurement of the ion density and ion velocity distribution much more accurately than before. Radiation from partially ionized impurities can lead to serious energy losses from experiments. Atomic collisions are important in producing an edge plasma which leads to a low production of these impurities. The major collision phenomena of interest involve atomic and molecular hydrogen, and helium collisions with ions electrons, and neutrals. Recombination due to charge exchange of neutral hydrogen and partially ionized impurities is an important effect as well. An understanding of the level of central radiation losses also involves detailed knowledge of the ionization, recombination, and excitation rates of multiply ionized impurities, as well as the transport processes of the impurities. Recent work on ionization and recombination is important in assisting us in understanding impurity radiation.

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INTENSITIES OF DIELECTRONIC SATELLITES OF Be-LIKE IONS

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Intensities I_s of dielectronic satellites to He-like ion resonance line due to dielectronic recombination mechanism of excitation are given by formula

$$i(\gamma-\gamma')=I_s(\gamma-\gamma')/I_{res}=\sum_{d_o} C(d_o)g_\gamma \Gamma(\gamma,d_o)A(\gamma,\gamma')/(A_\gamma+\Gamma_\gamma)$$

where $\gamma=d n l L S J$ is autoionizing upper state, d_o being the state of parent ion, A and Γ are the probabilities of radiative and Auger transitions. The coefficient $C(d_o)$ is proportional to initial state population $N_{Z+1}(d_o)$. If γ belongs to Be-like ion, d_o is $1s^22s$ or $1s^22p$. In low density (astrophysical) plasma only the state $1s^22s$ is populated and therefore $\gamma=1s2p^3$ is excited only through electrostatic level mixing. In high density laboratory plasma both states of are populated according to there statistical weights, intensities of satellites from $\gamma=1s2p^3$ being much greater.

We calculated partial probabilities of autoionization using the 1/Z expansion method for Be sequence Z=6-42. The results of $\Gamma(\gamma,d_o)$ in units $10^{13}s^{-1}$ for some Z are presented in Table. The comparison of $\Gamma(\gamma,1s^22s)$ and $\Sigma_l\ \Gamma(\gamma,1s^22l)$.

γ	$1s2s^22p\ ^1P_1$		$1s2s2p^2\ ^1P_1$		$1s2p^3\ ^1P_1$		$1s2p^3\ ^3P_1$		$^3P_2$
$Z \backslash d_o$	$1s^22s$	$1s^22l$	$1s^22s$	$1s^22l$	$1s^22s$	$1s^22l$	$1s^22s$	$1s^22l$	$1s^22s$
6	0,230	7,51	$6\ 10^{-5}$	8,31	0,017	23,8	0,528	24,1	0,528
10	0,235	7,68	0,002	8,31	0,014	23,6	0,456	23,9	0,456
14	0,257	7,79	0,014	8,33	0,013	23,5	0,413	23,6	0,364
18	0,334	7,95	0,063	8,37	0,012	23,2	0,361	23,0	0,253
22	0,517	8,21	0,204	8,50	0,010	22,7	0,296	22,1	0,205
26	0,821	8,60	0,503	8,74	0,009	21,7	0,234	21,7	0,172
30	1,19	9,06	1,03	9,12	0,009	20,6	0,185	22,0	0,137
34	1,55	9,53	1,74	9,60	0,009	19,7	0,146	22,4	0,103
38	1,85	9,86	2,54	10,1	0,008	19,2	0,116	22,5	0.075
42	2,09	10,3	3,29	10,5	0,006	19,2	0,091	22,5	0,053

The analogous data are calculated for all other levels for Be.

ELECTRON CAPTURE PROCESSES IN LOW ENERGY MULTICHARGED ION-ATOM COLLISIONS

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It is the aim of this paper to review the recent progress of this field. About two years ago, the situation was the following : On the experimental side, a large number of measurements for *total* cross sections was available which compared fairly well with various theoretical approaches confirming that the general features of the collision mechanism was well understood. However nearly nothing was known about the specific states populated by the electron capture processes preventing from a detailed comparison with theoretical predictions. Since then, the development of new ion sources allowed various spectroscopic techniques to be used, including VUV and X ray spectroscopy electron spectroscopy and energy gain spectroscopy (also called translational spectroscopy). As a general result, prediction of the dominant channels populated by *single* electron capture was confirmed at least for the simplest systems. But large discrepancies still exist for less important channels, even for the simplest one (or quasi-one) electron systems.A particular attention will be paid in the lecture to electron capture from hydrogen atoms.

The situation is, by for more complex, for *two electron* capture processes, for which very few theoretical predictions are available. Two types of processes dominate namely, population of autoionising states, and transfer ionisation. Then relative importance will be discussed using recent data on electron and translational spectroscopy.

CHARGE EXCHANGE COLLISIONS INVOLVING HIGHLY STRIPPED IONS : DISTRIBUTION AND ANISOTROPY OF FINAL STATE ANGULAR MOMENTA

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As electron capture by multicharged ions from atoms produces excited states of the projectile ion, many efforts have been devoted to the determination of the ℓ and m distribution of these excited states. This is clearly necessary to predict the deexcitation pattern. Experimentally, spectroscopic studied can give information on the ℓ distribution by observation of cascades.

In the low energy range where a molecular description of the collision is appropriate, transitions to the most populated excited state occur at the vicinity of a pseudo-crossing. We show in our work that the ℓ distribution is not determined by this primary process of electron capture. The Stark effect caused by the charge of the target after electron capture is strong enough to mix the various ℓ substates of a given n after the charge exchange has occured at the pseudo-crossing. However the ℓ distribution is not a statistical one. This can be explained by the constraint placed on the ℓ distribution by the m distribution. The latter is representative of the primary process of charge exchange and is much less influenced by the Stark effect. Once the m distribution is known, the ℓ distribution can be accurately determined by assuming a random distribution of the m population between the values of ℓ consistent with each value of m ("complete ℓ mixing model"). This effect shows the interest of the measurement of the m population.

We have measured main characteristics of n, ℓ, m final state distributions by x-ray spectrocopic techniques. Experiments have been performed at AGRIPPA in Grenoble for beams of bare or one electron Neon or Aluminium ions in the energy range 0.4 to 4 keV/u.

The m population of final p states (ℓ=1) has been determined by measuring the polarization of (1snp) $^1P \rightarrow 1s^2$ helium-like Lyman x rays. Such transitions are not depolarized by spin-orbit coupling and for the high n levels populated in these low velocity collisions they are very weakly affected by cascade effects. A high resolution Bragg crystal polarimeter was used in conjunction with a new type of position sensitive detector. Polarization rates around 50% have been found for instance for the most populated states (n=4,5,6) in 4 keV/u collisions of Ne^{9+} with H_2 in good agreement with Salin's predictions.

Mean ℓ values were extracted by a new method based on the determination of the ratios of cascade Lyman x rays (Lyman α/Lyman β/Lyman γ) appearing in the deexcitation of a population of nℓ excited states. Mean ℓ values of 2.2 and 3.0 were found respectively for $Ne^{9+} \rightarrow H_2$ and $Al^{12+} \rightarrow H_2$ cases.

SPECTROSCOPIC STUDIES (X, VUV) OF THE RADIATIVE DECAY OF LOW ENERGY CHARGE TRANSFER EXPERIMENTS AT THE AGRIPPA FACILITY

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It has been shown both theoretically and experimentally that single electron total capture cross sections -in the energy range 1 to 5 keV/A.M.U.- are quasi energy independant. They are essentially dependant on the projectile charge and on the target ionisation potential. Fc. a given ion-target pair, from classical theory and experimental rule, it is possible to assess which n_o is preferentially populated.

From radiative decay observed in the X and VUV domain, it is possible to determine the (n_o,l) substate populations and deduce their excitation cross sections.

We consider the case of different projectiles of charge +7 and +8 (N, O, Ne, Al).

For some of them, we show σ_{nl} for single capture from H_2 and He, as function of energy.

Pure double capture followed by radiative decay is shown to be effective. Observed transitions -of the same nature as dielectronic recombination satellites- are the signature to this process.

Finally, in the case where energy levels are not known, since capture is a selective process, radiative decay is a means for new basic spectroscopic studies ; examples are shown : Al^{8+} capturing one electron from H_2.

SUBSHELL SELECTIVE ELECTRON CAPTURE CROSS SECTIONS FOR COLLISIONS BETWEEN HIGHLY CHARGED LOW Z IONS AND H(1s)

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ABSTRACT NOT AVAILABLE

RADIATIVE CORRECTIONS IN HIGHLY IONISED ATOMS

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A review of the theory of radiative corrections in highly ionized atoms will be given. Comparison of theory and experiment in these atoms provides an important test of the theory of strongly bound electrons.[1] For one-electron atoms, energy level separations predicted by quantum electrodynamics among the n=1 and n=2 states of hydrogenlike atoms with nuclear charge Z in the range 10-40 have recently been tabulated.[2] This tabulation is based on a complete nonperturbative calculation of the self energy.[3] In highly ionized atoms with more than one electron, the hydrogenic radiative level shifts provide a first approximation to the few-electron radiative level shifts. Uncalculated corrections due to multielectron effects in the radiative corrections give the largest known uncertainty in the theory of two-electron atoms. Various approaches to this problem and the prospects for further improvements will be described.

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ENERGY LEVELS AND RELATIVISTIC E1-M1 TWO PHOTON TRANSITIONS IN U^{90+} *

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It has recently become possible to produce beams of very highly ionized atomic systems such as two-electron U^{90+}.[1] In such systems, relativistic and QED effects become too large to be treated as small perturbations, and higher order radiative processes that are normally considered to be negligibly small can play an important role. As a particular example, the state 1s2p $^3P_0$ can decay by ordinary E1 transitions to the 1s2s $^3S_1$ state, or by the exotic E1-M1 two photon process to the $1s^2$ $^1S_0$ ground state. The rate for the E1-M1 process is calculated to be 5.68×10^9 sec^{-1}, which is about 25% of the total decay rate. A very efficient relativistic finite basis set method is used to perform sums over complete sets of positive and negative frequency virtual intermediate states.

The paper will also discuss methods used to calculate the energy levels of relativistic very heavy two-electron ions.

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RELATIVISTIC ATOMIC STRUCTURE CALCULATIONS FOR HIGHLY IONIZED SYSTEMS

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The increasing availability of comprehensive computer packages for the calculation of atomic structure and properties including relativistic effects [1-5] has made it possible for the theorist to make ab initio predictions of atomic properties of growing precision. This theme will be illustrated with a series of examples including comparisions of theoretical results with data drawn from beam-foil spectra, laboratory plasmas and solar flares. Wavelengths of lines of Fe XXIII - XXV on the long wavelength side of 1.85 Å have been predicted with relative separations agreeing with experiment to within 0.1 mÅ using the programs devised by the author and collaborators[4] which have also been used to compute radiative transition probabilities[10].

Measurements[7] of the wavelengths of $1s2s\,^3S - 1s2p\,^3P$ transitions in two-electron ions have been made with a view to testing relativistic atomic structure theory, including radiative corrections, in ions with nuclear charge up to Z = 26. Recent calculations by Hata and Grant[8] and by Drake and Goldman[9] are able to reproduce the experimental wavelengths to within the quoted errors for most ions with $Z \leq 10$. The experimental errors for larger values are not yet small enough to detect any systematic departures from the theoretical predictions, so that current methods of approximation[8,9] are adequate for the time being.

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THE STATUS OF NOVEL ION SOURCES

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The developments of the different ways of getting highly stripped ions, excluding accelerators, are reviewed and peculiarly, the new possibilities of ECRIS ans EBIS.

CRYOGENIC EBIS SOURCES AND ASSOCIATED ION PHYSICS AT JINR

E D Donets

JINR, Dubna

ABSTRACT NOT AVAILABLE

LIFETIME MEASUREMENTS USING BEAM-FOIL SPECTROSCOPY

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The current status of beam-foil lifetime measurements will be reviewed. A survey of the advances that have been made since the 1981 Laval Conference will be presented, together with a summary of some current problems. Topics that will be discussed include

i) developments in ion sources for beam-foil spectroscopy;
ii) techniques for the analysis of beam-foil intensity decay curves;
iii) recent studies of doubly-excited states; and
iv) a progress report on the study of f-value trends along the Na I, Cu I, Ag I, Zn I and Cd I isoelectronic sequences.

FAST-BEAM SPECTROSCOPY AT TANDEM ENERGIES

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The main topics of the talk are those which are apparent from the literature since the previous conference on fast-beam spectroscopy, held at Laval (Canada) in 1981. These areas of recent and current interest are

- "Complete" spectra of few-electron systems, up to high-lying levels.
- Fine structure measurements in singly-excited few-electron ions. Here n=2, n=0 transitions in He I and Li I like ions from F to Kr have been measured aiming at a precision which is sufficient to check various QED contributions to the term structure.
- Precision determination of n=1 - n'=2 transitions aiming at the n=1 ground state Lamb shift in one- and two-electron systems.
- The satellite lines which disturb these measurements result from multiply-excited few-electron systems which are of interest for atomic structure theory and for plasma diagnostics.
- Transitions between multiply-excited high-spin states reveal details of the structure of such systems, as there are fine structure and differential metastability against autoionisation.
- Isoelectronic sequences of many-electron systems have been studied to find out about their systematics. Among these the Ne I like ions have been of particular interest because of envisaged UV laser applications.

Examples for each of these types of experiment will be presented and discussed.

SOME CURRENT PROBLEMS IN BEAM FOIL SPECTROSCOPY

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Developments in several areas of current research in beam foil spectroscopy will be described. The use of tilted foils to produce alignment and orientation excitation asymmetries will be reviewed and the current knowledge of the dependence of these asymmetries on various experimental parameters (energy, foil tilt angle, observation geometry, etc.) will be examined. The creation and utilisation of alignment and orientation for the study of atomic and nuclear structure properties will also be discussed, with emphasis on applications to multiply ionised systems. A number of examples of methods for obtaining essentially cascade-free lifetime measurements that exploit specific asymmetries in excitation or decay will be presented and applications to lifetime determinations for forbidden and inhibited transitions will be given. Some recent spectroscopic studies of highly ionised members of isoelectronic and homologous systems will also be reported.

ION SURFACE INTERACTIONS

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ABSTRACT NOT AVAILABLE

SOME BEAM-FOIL EXCITATION MECHANISMS

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Various proposed models for beam-foil excitation processes are reviewed and compared to experimental data where available.

CHARGE TRANSFER PROCESSES IN ASTROPHYSICAL PLASMAS

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Charge transfer processes involving multiply-charged ions modify the ionization structure of astrophysical plasmas and exert a major influence on plasmas created by the absorption of high frequency radiation. As a recombination mechanism, charge transfer suppresses the higher ionization stages. In hot plasmas, charge transfer ionization may enhance the abundances of highly charged systems. Charge transfer excitation also occurs and the resulting emission lines provide a unique diagnostic probe of the neutral content of the plasma, the ionization distribution and the nature of the ionization source.

Several examples of the role of charge transfer as a recombination, ionization and excitation mechanism in astrophysical plasmas will be presented.

THE SPECTROSCOPY OF HIGHLY IONIZED ATOMS

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New sources of highly ionized atoms at both very high energies and very low energies create new opportunities for spectroscopy. Uranium 92+ was produced in 1983 and is already being used for spectroscopy. For lighter elements, secondary-ion recoil sources, electron cyclotron-resonance sources, and electron-beam ions sources are becoming increasingly available as spectroscopic sources of low-energy highly charge state ions.

The spectra of highly ionized atoms features large relativistic, quantum electrodynamic, and nuclear effects. In hydrogenlike- or few- electron highly ionized atoms theories of these effects may be directly confronted. Some of the present experiments using these new sources will be reviewed and speculations on possible new measurements will be offered.

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Laser Resonance Measurements in Highly Ionized Atoms

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Recent experiments using laser techniques to measure transition intervals in highly ionized atoms are reviewed. This includes (1) measurements of the n=2 Lamb Shift in hydrogenic phosphorus, sulphur and chlorine and (2) measurements of the $2^3P_1-2^3P_2$ finestructure interval in helium-like flourine.

SPECTROSCOPY OF MEGAVOLT ENERGY IONISED ATOMS IN LASER PLASMA

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The broadening of the resonance line of the helium-like ion of phosphorus emitted by a laser plasma is discussed. The broadening is interpreted as a Doppler frequency shift of the emission of high-energy ions. The energy spectrum of these fast ions is determined. The temperature of the electrons responsible for the ion acceleration is estimated.

FUNDAMENTAL AND INCIDENTAL LIMITS ON THE SPECTROSCOPY OF SINGLE ELECTRON IONS

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Precision measurements of spectra from one-electron ions are principally focussed on tests of Q.E.D. corrections to the energy levels implied by the Dirac equation. Even though spectroscopic tests in atomic hydrogen itself and determination of the anomalous moment of the electron have reached impressive levels of refinement and demonstrate equally impressive consistency between experiment and theory, exploration of the Z-dependence of such comparisons remains of interest. Fundamentally, such "Lamb-shift" experiments are characterized by and are limited by some "Q-value" determined by the magnitude of the Q.E.D. shift, S, in relation to a line-width parameter, γ. Such Q-values are rather small for the traditional $\Delta n=0$ experiments, regardless of Z. Substantial improvement in this regard is available if one studies $\Delta n=1$ transitions, but in these cases there is a substantial, though largely incidental, penalty in loss of "leverage" in the measurement. Additionally, and also incidentally, the earliest example of such $\Delta n=1$ experiments have suffered from various combinations of Doppler troubles and spectator electron perturbations. Only in one very recent effort has it been possible to bring both of these problems under simultaneous control thereby inviting consideration of a still more refined level at which fundamental limitations again appear dominant. One can further deal with the dominant intrinsic limitation occurring at this stage in principle but at the cost of still more refined measurement technology which appears to be practical but to lie in the future.

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CHARGE EXCHANGE SPECTROSCOPY FOR PLASMA DIAGNOSTICS

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Charge-exchange spectroscopy has been recognized for several years as a potentially useful tool in the study of fusion plasmas,[1,2] and its employment is now becoming widespread. Many fusion devices are equipped with atomic hydrogen beams for heating or for diagnostic probing. These have been exploited to determine the concentrations of fully stripped light ions (C^{6+}, N^{7+}, O^{8+})[3,4] from the spectral lines emitted subsequent to charge transfer from H^0 into excited states of the hydrogenic impurity ions. Effective cross sections for this process are computed from calculations of n,ℓ excitation by collisions,[5-7] and by cascading. At beam energies below 35 keV, the range in which most experiments have been done, computations show that the charge exchange process primarily populates the high angular momentum states of two excited levels. The strongest lines are, therefore, predicted to be emitted in the sequence of $\Delta n = 1$ radiative decays to the ground level. Neither state mixing by electric and magnetic fields nor by collisions appears to seriously affect this conclusion for the experiments performed so far. Although different types of calculations produce absolute cross sections that can disagree by a factor of 2, the relative intensities of the $\Delta n = 1$ transitions are computed to agree within 15%. As a result, these lines can be used for *in situ* measurements of the response of a spectrometer over a wide wavelength range – 102 Å to 1165 Å in the ISX-B tokamak.

The charge-exchange excited (CXE) lines are also useful for determining plasma rotation and ion temperatures. The emissions, which can be produced even at the center of a high-temperature discharge, have wavelengths long enough that Doppler shifts and broadenings are measurable with spectrometers of modest size. Such experiments have been done with lines from intrinsic impurities[8] or from helium which is deliberately seeded into plasmas.[9,10]

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SUPERHEAVY QUASI ATOMS AND QUANTUM ELECTRODYNAMICS IN STRONG FIELDS

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In collisions of heavy ions with $Z = Z_1 + Z_2 > 109$ and with bombarding energies below the nuclear Coulomb barrier superheavy quasi atoms are created for a short period of $\tau \sim 10^{-20}$ s. The spectroscopy of rather strongly bound electron states in these exotic systems is illustrated. Electron excitations in quasi atoms with total nuclear charge numbers in the range $117 \leq Z \leq 188$ are considered. Theoretical results are compared with recent measurements on the K-hole production, δ-electron distribution, quasimolecular X-ray spectra and the positron emission. Radiative corrections to the electron binding energies predicted by quantum electrodynamics are extensively discussed for hydrogen-like atoms in the known periodic system as well as for superheavy elements.

During collisions of very heavy nuclei with a combined charge $Z > 173$ the 1s-state enters as a resonance the lower continuum of the Dirac-Hamiltonian. In pure Rutherford scattering of the heavy ions no qualitative indication for the filling of the dynamically created K-hole by the spontaneous positron creation process is expected, but the study of heavy-ion collisions with nuclear time delay due to the attractive nuclear force promises clear signature for this decay of the vacuum. Corresponding experimental results show evidence for this transition from the neutral vacuum to a charged ground state and for the existence of long living nuclear molecules.

Within the framework of a semiclassical description we furthermore investigate the influence of nuclear reactions on various atomic excitation processes. It is demonstrated that the spectra of emitted δ-electrons and positrons may be employed as atomic clock for nuclear reaction times.

POPULATION INVERSIONS AND GAIN FOR X-RAY LASERS

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A currently challenging research problem involving the spectroscopy and physics of highly ionized atoms is the development of laser amplifiers for wavelengths shorter than 1000 Å and extending into the x-ray spectral region. High densities are needed to achieve sufficient gain per unit length to compensate for inefficient cavities in this region of the spectrum; while at the same time non-equilibrium population distributions are required to achieve the necessary inversions. Several pumping methods of current interest will be discussed along with measurements of inversion densities and gain. The presentation will conclude with an overview of current activities in this area, and projections for future possible directions and the problems to be solved.

HEAVY ION BEAM PUMPED LASERS

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Particle beams with energy per particle ranging from a few keV to greater than 1 GeV have been used to pump gas lasers. Well-focused high energy heavy ion beams have a short range, low range straggling and high specific energy loss which increases with the square of the effective charge. They can be used to pump a small cylindrical volume which can be well-matched to the optical axis of a laser resonator. Results obtained to date will be described with both cw and pulsed particle beams; and possible extensions using heavy ion storage rings will be considered.

Ionization of fast foil-excited ion-beams in electromagnetic fields

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Fast ions traversing thin solid targets emerge in a variety of excited electronic states. This aspect of ion-solid interactions has made it possible, through beam-foil spectroscopic techniques, to explore the electronic states of a wealth of atoms.[1] Over the course of the last decade, these studies have concentrated mostly on the low-lying excited states of few-electron high-Z atoms. Because of the comparatively small decay rates of higher excited states,[2] and because of the low yields of such states[3], there has been relatively little spectroscopic work involving principal quantum numbers n>10-15. It has, however, been known for several years that cascades from very high-lying levels play an important role[4] in determining the observed time dependence of measured decay curves. Studies of delayed K-x-ray emission have suggested surprisingly large yields of high Rydberg states and unusual quantum-state populations[5]. These observations have led to speculation about possible formation mechanisms which might be responsible for producing these high Rydberg states. In an effort to better understand these results, we have conducted an intensive series of experiments aimed at measuring the yields and quantum-state populations of high-Rydberg-state atoms formed by beam-foil excitation of fast-ion beams. These yields of electrons produced by field ionization of these atoms are compared for different projectiles and beam energies. Various field arrangements were used.

From the measured yields we find continuity of the capture cross section across the ionization threshold. In measurements with microwave fields, where the applied and stray fields may tend to produce statistical repopulation of the substate population, we find a $1/n^3$ quantum-state population. This is also consistent with measurements of continuum electron cusp shapes which also suggest a $1/n^3$ scaling rule for high-Rydberg-state atoms. The states which we observe include coherently excited superpositions of Stark levels. These states could, in fields where the coherency is preserved, affect measurements of the quantum-state population.

The physical picture which emerges from these observations is that the Rydberg states are formed by capture into highly excited bound states, by the projectile, of nearly free electrons which move through the foil with the beam, correlated in space and in time.

These observations have an important impact on several fields of research. It seems evident from the results that, in interpreting observations on convoy electrons, it is necessary to take into account the possible contributions of electrons stemming from the ionization of projectile Rydberg atoms in the spectrometer field.

The beam-foil cascade problem is another area where the observations should be important. Cascade calculations of the yield of delayed x-rays from foil-excited ion beams are quite sensitive to the assumed quantum-state populations in the beam, particularly with respect to angular momentum. The observed phenomena offer a new and potentially powerful technique for studying the excitation mechanisms which produce high Rydberg states of fast projectiles as they excit solids. As such they represent a useful probe of both the ion-solid and ion-surface interactions.

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THE PHYSICS OF ION BEAM FUSION

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The use of intense beams of ions from accelerators to heat and compress deuterium-tritium to thermonuclear ignition conditions is now a favoured alternative to laser-driven fusion as a possible source of electricity production. Following a comparison of the relative merits of lasers and accelerators, the presentation looks at the important physics aspects of ion beam fusion. Three main areas of activity can be defined, namely accelerator design, beam transport physics and ion-plasma interaction physics for target design. Progress in each of these areas is described and possible future milestone experiments are discussed.

POSTER SESSION A

ABSTRACTS 28 - 71

MEASUREMENT OF THE IONIZATION PROBABILITY OF THE $1s\sigma$ MOLECULAR ORBITAL IN HALF A COLLISION AT ZERO IMPACT PARAMETER

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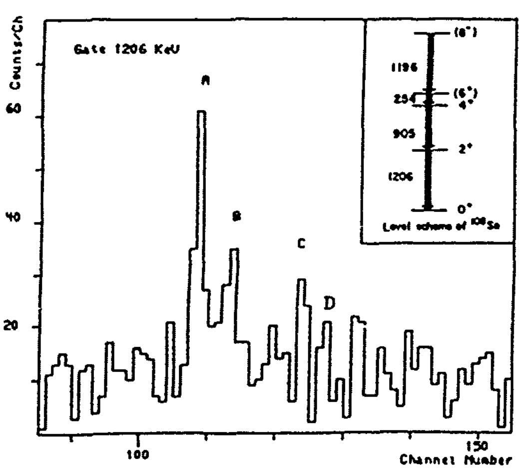
When two heavy ions collide to make a nuclear reaction the interacting system is due to excitation caused simultaneously by atomic and nuclear processes. Part of the nucleus excitation is released by emission of gamma rays, or by an internal conversion process leading to emission of K X rays characteristic of the reaction product. Internal conversion competers strongly with γ ray emission for low energy transitions. This takes place after complete slow down of the residual nucleus in the target. On the contrary atomic vacancies created or present in the entrance channel of the nuclear reaction will be transferred to the reaction products and will decay within a time of the order of the K-shell vacancy lifetime 10^{-17}s. In this case the reaction products will have the full recoil velocity. In the reaction $^{58}Ni + {}^{53}Fe$ at E_{Lab} 230 MeV we performed a coincidence measurement between X rays detected at zero degrees and gamma rays detected in six Ge(I) detectors. Fully doppler shifted Sn X rays, due to the decay of atomic vacancies, are observed when gated on characteristic γ-rays of the ^{108}Sn. The prompt X-ray spectrum gated on the 1206 keV γ-ray in ^{108}Sn is shown in fig. 1. Two X-ray lines labelled A and B clearly show up in this figure. The lines C



and D are the respective K_β X rays associated to A and B. The line A, the energy of which corresponds exactly to the energy of the Sn K_α X ray, is due to an internal conversion (IC) process occuring in the decay of the excited ^{108}Sn residual nucleus. The energy of the line B corresponds to the fully doppler shifted energy of a Sn K_α X ray. In the same way identical X-ray spectra are found in coincidence with the other ^{108}Sn γ-ray transitions except for the 254 keV line for which the unshifted Sn X-ray does not show up. Consequently the number ($P_{1s\sigma}$) of vacancy present in the $1s\sigma$ molecular orbital before the nuclear reactions can be obtain directly from the relative intensities of lines A and B, knowing the internal conversion coefficient of the 254 keV transition. We found $P_{1s\sigma} = 0.03 \pm 0.01$.

A RENEWED STUDY OF BORON II

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The energy levels and f-values of B II have been studied by several authors but a number of problems still prevail. For example, the f-values of the $2s^2\ ^1S$ - $2s2p\ ^1P$ resonance transition, as determined in beam-foil experiments, are significantly lower than the theoretical values. This may be due to a very unfavorable cascade situation which complicates the analyses of the experimental data.

Furthermore, the experimental energy of the $2s3s\ ^1S$ level, based on the classification of a line at 1608 Å as the $2s2p\ ^1P$ - $2s3s\ ^1S$ combination, see e.g. (1), is not supported by the superposition-of-configurations (SOC) calculations of Weiss (2), which in all other cases are in excellent agreement with the experimental material (1).

To clarify such problems we have re-examined the spectrum of B II, using classical emission spectroscopy as well as the beam-foil method. The spark spectra of boron (300 - 2500 Å) were recorded at Lund, using a 3 m normal incidence spectrograph, whereas beam-foil spectra (1100 - 2000 Å) were taken in Tucson (beam energies 0.5, 0.75 and 1.0 MeV) using a 0.5 m Seya-Namioka monochromator.

Boron is difficult to excite in classical spectroscopy and the problems were further complicated by the presence of various impurity lines. The beam-foil method does not have these shortcomings. Despite the lower resolution the beam-foil data thus complement those from spark spectra.

The region of particular interest (1560 - 1620 Å) was found to contain a number of lines not reported earlier. Wavelengths and decay times for several of these new lines were determined.

The lifetime of the $2s2p\ ^1P$ level was measured at several ion energies. For a detailed analysis of the cascading situation, the decays of the $2p^2\ ^1S$, $2p^2\ ^1D$, $2s3d\ ^1D$ and some other levels were also measured and the ANDC method was applied. The new data tend to agree with modern theoretical results.

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POPULATIONS OF np TERMS IN DEUTERIUM ATOMS EMERGENT FROM CARBON FOILS BOMBARDED WITH D^+, D_2^+, AND D_3^+ IONS.

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We have measured relative beam-foil populations of 2p, 3p, and 4p terms in D^0 as a function of the projectile energy ($20 \lesssim E/M \lesssim 500$ keV/amu) for D^+, D_2^+, and D_3^+ ions emerging from carbon foils of various thicknesses ($\simeq 2 - 20\ \mu g/cm^2$).

With D^+ projectiles, the np populations reach their equilibrium values even in the thinnest foils used. We compare the dependence on energy of these populations to the equilibrium neutral fraction variation for hydrogen (deuterium) beams emerging from a carbon foil and deduce some information concerning beam-foil excitation mechanisms[1].

When fast molecular hydrogen (or deuterium) projectiles (H_2^+, H_3^+, D_2^+, D_3^+) bombard thin foils, it is well known that the neutral fraction and the beam-foil populations (per incident proton or deuteron) are greater than those obtained with atomic projectiles (H^+, D^+)[2-7] and that the dwell time t, i.e., the time spent by the projectile in the foil, plays a vital role. In this work we consider only the dwell time region $t > 1.5 \times 10^{-15}$s. We study the variation of $R_{2p} = I^{molec}/I^{atom}$ (I^{molec} and I^{atom} are the Ly-α intensities per incident deuteron observed with molecular and atomic projectiles of the same velocity, respectively) with the projectile energy per nucleon (E/M) and the thickness (T) of the foil. For a foil of given thickness R_{2p} increases with E/M and reaches a saturation value R_∞ which decreases when T increases. These results, in agreement with our previous measurements using hydrogen projectiles[6], indicate that t is not the only parameter relevant to molecular effects. Comparisons are reported between R_{2p} values obtained (a) with H_2^+ and D_2^+ projectiles and (b) with D_2^+ and D_3^+ projectiles, using foils of given thickness ($T \simeq 3,5$, and $18\ \mu g/cm^2$) and projectiles of different energies. Ratios R_{np} (E/M) are also measured for n = 3 and 4 using Ly-β and Ly-γ radiations and compared to R_{2p} values. An interpretation for some of our results is proposed.

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A DENSE ELECTRON TARGET FOR ELECTRON-ION COLLISIONS

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A new high current (0.5 A), high density (0.3 A/cm²) electron gun has been designed for crossed beams electron-ion-experiments to yield high signal to background counting rates in the energy range 10 - 1000 eV. Great computational effort has been spent to assure a uniform electrostatic potential in spite of the high electronic space charge. Trapped ions can be used to compensate this space charge, because their contribution to the counting rate is well discriminated below the threshold of the process to be studied. The overlap integral is determined by sweeping the whole electron gun perpendicular to both beams over the ion beam, which is possible, because the interaction region potential extends in perpendicular direction of both beams and sweeping therefore does not affect ion beam transmission.

The experiments now are in progress with an improved vacuum environment. Results will be presented on recent cross section measurements for the ionisation of singly and mutliply charged krypton and antimony ions.

EXPERIMENTAL CROSS SECTIONS FOR TWO-ELECTRON CAPTURE INTO NITROGEN AUTOIONISING STATES IN N^{q+} (q = 6,7) ON He AND H_2 COLLISIONS, AT 10.5 qkeV

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It has been recently shown[1] that capture of two electrons occurs into highly two-electron excited autoionising configurations (nl,n'l') in the collision between N^{q+}(q = 6,7) and a two-electron target (He,H_2) at low energy ($v \cong 0.4$ a.u.). Preliminary results concerning cross-sections for two-electron capture into various (n,n') configurations will be presented at this conference. Assuming isotropic angular distributions, total cross-sections, summed over n and n', have been estimated as given in the table :

	N^{7+}-He	N^{7+}-H_2	N^{6+}-He	N^{6+}-H_2
$\sigma_{tot}(10^{-16} cm^2)$	0.7 ± 0.2	2.2	0.4 ± 0.1	1.9

These values, being more than one order of magnitude lower than one-electron capture cross-sections[2], agree with gain energy spectroscopy results[3] obtained at 1 qkeV but strongly differ from theoretical prediction for O^{8+}-He[4].

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ELECTRON CAPTURE INTO RYDBERG STATES IN COLLISIONS BETWEEN MULTIPLY-CHARGED IONS AND HYDROGEN

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We investigate the substate distribution $\sigma_{\ell m}$ in Rydberg manifolds ($n \simeq 10$) following the charge transfer reaction

$$C^{6+} + H(1s) \rightarrow C^{5+}(n) + H^{+}$$

at high velocities $v \gtrsim 1$ a.u. A modified Continuum Distorted Wave (CDW) approximation is developed that takes explicitly into account final-state interactions with the residual target ion in the exit channel. Stark mixing of different angular momentum states in the target field can be incorporated analytically using the PCI model[1]. The resulting CDW-PCI approximation[2] leads to considerable changes in the (ℓ,m)-distribution compared with a standard CDW calculation. We observe a shift of the ℓ distribution to lower ℓ values (Fig. 1). This correction is of crucial importance at intermediate velocities ($v \simeq 1$). In the limit of asymptotically high velocities ($v \rightarrow \infty$) the CDW-PCI calculation approaches the standard CDW result.

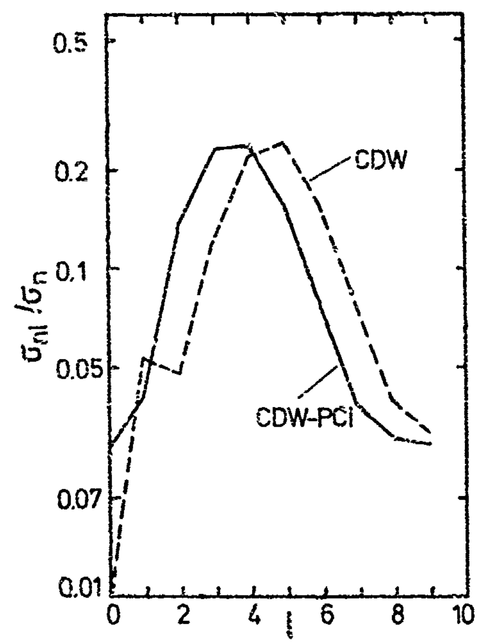

Fig. 1: $\sigma_{n\ell}/\sigma_n$ in $n = 10$ following $C^{6+} + H(1s) \rightarrow C^{5+}(n) + H^{+}$ at $v = 1$ a.u.

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MEASUREMENTS OF THE POLARIZATION OF RADIATION EMITTED BY FAST ARGON IONS SCATTERED BY CLEAN AND COATED SURFACES

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Singly-charged 60 keV argon ions were scattered at small angles of incidence (1-3 deg.) from a stainless-steel solid target. Light from the fast ions emitted perpendicularly to the beam direction from a small region of space just past the end of the target was polarization analyzed, monochromatized and detected. The relative Stokes parameters were measured.

Light from the fast ions was collected with a 2 in. diameter lens, which sent parallel rays through a stressed-quartz rotating quarter-wave plate, and a linear polarizer, to a 1 m monochromator and EMI 9789Q photomultiplier. The quarter-wave plate stress was separately adjusted with an optical calibration system. This plate is rotated with a stepping motor. The photomultiplier pulses were collected in a multichannel analyzer. A Fourier transform of the signal variation with rotation angle provides measures of the relative Stokes parameters following subtraction of the independently measured background.

The transition near 4610Å of Ar II was selected for study due to a relatively large (>36%) total polarization fraction, largely (≈35%) due to circular polarization when scattering occurred from a clean target. The observed polarization fraction depends on the location of the observation region relative to the target. The target surface was parallel to the ion beam in a baked ultrahigh vacuum chamber pumped by ion and cryogenic pumps. The base pressure of the chamber under operating conditions was 10^{-9} Torr. The ion beam was electrostatically deflected onto the target, which was cleaned by sputtering using the incident ion beam, resulting in a stable polarization level. The beam current was $\gtrsim$ 10 microamps into a suppressed Faraday cup.

Introduction of gases such as N_2 and H_2, at pressures between 10^{-7} and 10^{-6} Torr reduced the circular polarization fraction to ≈ 25% and 30% respectively, essentially independent of the ion incidence angle, or of the pressure above 10^{-7} Torr. Changes in collected light levels associated with gas adsorption on the surface had relative magnitudes differing from the polarization changes. Removal of the gases during ion bombardment resulted in a return to the original polarization level within ≈ 600 sec.

The results are interpreted as a modification of the excited level orientation due to scattering from surface atoms, which should dominate at this ion energy.

This research is supported by the National Science Foundation and by the Texas A&M Center for Energy and Mineral Resources.

SUBSHELL-SELECTIVE ELECTRON CAPTURE IN SLOW COLLISIONS OF He^{2+} and C^{3+} WITH ATOMIC AND MOLECULAR HYDROGEN

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Electron capture by slow ($0.1 < v < 0.6$ a.u.) He^{2+} and C^{3+} ions from atomic (and molecular) hydrogen has been studied by means of photon spectroscopy.

The ion beams (produced by an ECR ion source) were crossed with a partly dissociated hydrogen beam, produced by a radiofrequency discharge source. The typical target thickness used was 10^{13} at/cm^2, at a dissociation degree in the collision center of 70 % or more. We observed the VUV-radiation resulting from the decay of the excited ion states produced by electron capture, in the wavelength range 10 - 250 nm, with two absolutely calibrated VUV-monochromators. Details about the calibration of target composition and density and about the sensitivity calibration of the monochromators will be shown.

For the systems He^{2+}- H, H_2 we have measured the HeII 2-1, 3-1 and 3-2 transitions at 30.4, 25.6 and 164 nm respectively. From these we deduced σ_{2p}, σ_{3p} and(σ_{3s}+ σ_{3d}) as shown in fig.1.The sum of these cross sections is equal to σ_t- σ_{2s}, and is in excellent agreement with previous data of other authors[1,2] (fig.2), illustrating the reliability of our method. A detailed comparison is made with various calculations.

The results for the system C^{3+}- H are compared with recent data of McCullough et al.[3] obtained by energy gain spectroscopy.

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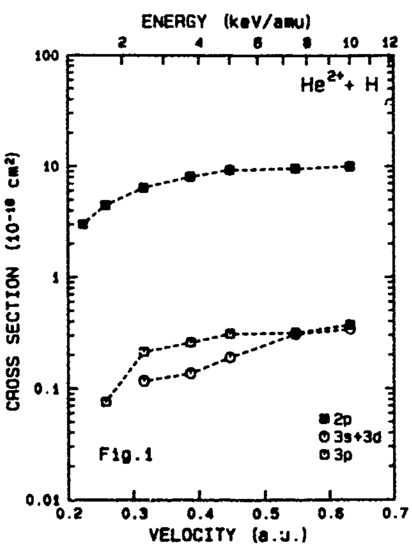

Fig.1

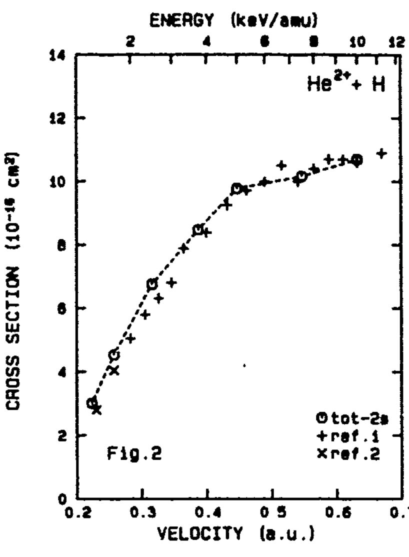

Fig.2

ABSOLUTE CROSS SECTIONS FOR COLLISIONS BETWEEN LOW-ENERGY Ar^{q+} AND Ar

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We here report absolute cross sections $\sigma^{s}_{q,q-r}$ for collisions between low-energy (1.8q keV) argon ions in a variety of charge states ($1 \leq q \leq 9$) and neutral argon.

To produce the argon ions we have modified a technique originally developed by Cocke et al.[1], where recoil ions with low energies and high charges are created when a high-energy beam is led through a gas target. In our case the high-energy ions come from the 225-cm cyclotron at the Research Institute of Physics. The recoil ions, used as projectiles in the collisions under study, are accelerated in electrostatic fields before they reach the collision cell. In previous experiments of this kind the charges of the projectiles before the collision (q) were determined from their flight times (proportional to $q^{-1/2}$) while the charges after the collision (q-r) were measured by deflecting the ions in an electrostatic analyser. We have replaced the analyser by a second acceleration field and determine both the initial and the final charges from the flight time. Since sweeping an analyser implies that most of the ions are discarded we have, compared to an earlier set-up[2], been able to increase the count rate about 30 times in this way. Another advantage is that neutralised projectiles can be detected. Also the charges of the ionised target atoms (s) are obtained from time-of-flight measurements and are registered in coincidende with the projectile ions.

With this method we have determined absolute cross sections for a large number of charge-transfer and transfer-ionisation processes where the projectile ions have picked up between one and five electrons while the target atoms have lost up to five electrons.

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ELECTRON IMPACT IONIZATION OF N^{4+} AND N^{5+}

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Up to now, the crossed electron-ion beam experiments have been restricted to ion charge states lower than 6 produced by PIG or EBIS sources. Powerful ECR ion sources have been developped so that beams of higher change states are now available for experiments. In order to measure total ionization cross-sections a crossed electrons-ion beam has been built, applying the animated crossed-beam method (1).

The ion beam is extracted from the ECR source by a voltage of a few keV. A Wien filter analyses the ion beam before the crossing with the electron beam. After the crossing, a subsequent magnetic field separates ions of charge state higher than this of the primary beam ions. This primary beam is collected on a Faraday cup. Secondary ions are detected by a channelplate detector.

First results (Fig. 1)* have been obtained for the single ionization of the Lithium like ion N^{4+} for which both theoretical and experimental data have been published. There is good agreement between experimental data of Crandall et al (2) (represented by the recommended curve of Bell et al (3) and the theoretical results of Jakubowicz (4). Our data are higher than those by about 10% at the maximum and the contribution of auto ionization is clearly seen.

For the helium-like ion N^{5+}, preliminary data have shown a significant contribution of metastable ions well below the threshold for ionization of the ground state. As estimated from the semi-emperical Lotz formula, the population of the long-lived 2^1S and 2^3S is 3% which means that long-lived metastable ions are easily produced in the ECR source.

* Results will be presented at the Conference.

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SUBSHELL-SELECTIVE ELECTRON CAPTURE IN SLOW C^{4+}, N^{5+}, O^{6+} - H, H_2 COLLISIONS

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We have determined absolute subshell-selective cross sections σ_{nl} for one-electron capture by slow ($0.1 < v < 0.6$ a.u.) C^{4+}, N^{5+}, O^{6+} ions from atomic (and molecular) hydrogen, by means of photon spectroscopy.

The multiply charged ion beams (produced by an ECR ion source) were crossed with an atomic hydrogen beam. The VUV-radiation resulting from the decay of the excited ion states produced by electron capture was detected with absolutely calibrated monochromators.

For all systems studied we find that the total capture cross section does not depend strongly on the impact velocity, and is in good agreement with published results from other authors[1,2] (see e.g. fig.1). For C^{4+}, capture takes place dominantly into the n=3 shell, for O^{6+} into the n=4 shell, whereas for N^{5+} capture is distributed over both the n=3,4 shells. This holds for the H as well as the H_2 target.

The nl-subshell selective cross sections depend strongly on the impact velocity. For $v > 0.5$ a.u. the highest possible l-subshell within each n-shell is preferentially excited and the distributions for H and H_2 are very similar. However, towards low velocities, the l-distribution is strongly depending on the particular system. The results for $\sigma_{nl}(n=3,4)$ in C^{4+} - H collisions are compared with recent calculations by Fritsch and Lin[3] (fig.2), who used an atomic orbital expansion technique.

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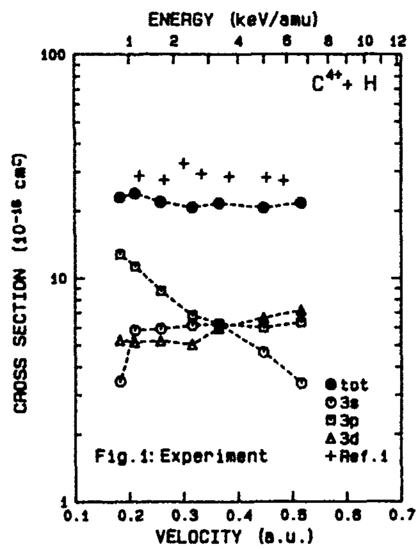

Fig.1: Experiment

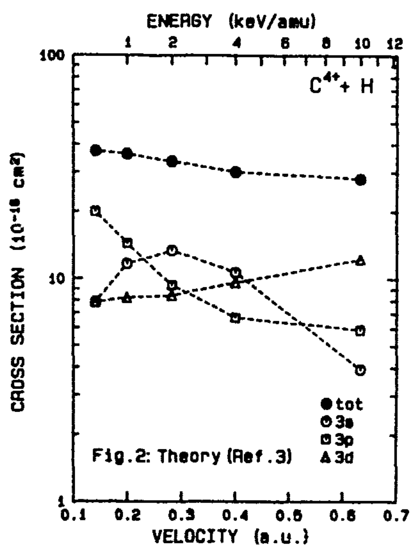

Fig.2: Theory (Ref.3)

SURFACE PHYSICS WITH MULTIPLY CHARGED IONS

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The lack of experimental data on the interaction of multiply charged ions with solid surfaces (metals, insulators) has led to start a program on surface physics, using beams from the ECR ion source at the KVI.

In a simple set-up with a target manipulator and an electrostatic analyser, a polycrystalline Tungsten surface will be bombarded with Ar^{q+} ions ($1<q<10$) in order to study the energy distribution of the resulting Auger electrons. In addition we intend to measure the charge state distribution of the outcoming (partly) neutralized Ar ions. In this way it is hoped to get information about the several steps of the neutralization processes.

A separate collision chamber is presently under construction; here experiments with multiply charged ions on insulator materials will be performed to see whether the process of Coulomb explosion exists.

Measurements on the Tungsten target have started in April. First results will be shown.

THE ECR SOURCE FOR MULTIPLY CHARGED IONS, AND ASSOCIATED EQUIPMENT AT THE KVI

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The ECR ion source at the KVI is of the Minimafios type; part of the time it operates as external heavy ion source for the cyclotron. The remaining time, that is about 1/3, it is available for atomic and surface physics. The source area is well shielded from the cyclotron vault. Presently, three experimental stations are available:

i) A collision chamber for electron capture spectroscopy, equipped with gas targets (also atomic H, and Li) and VUV monochromators. This set-up was constructed by the group of F.J. de Heer, D. Dijkkamp c.s. (AMOLF, Amsterdam) and is in operation since November 1982.

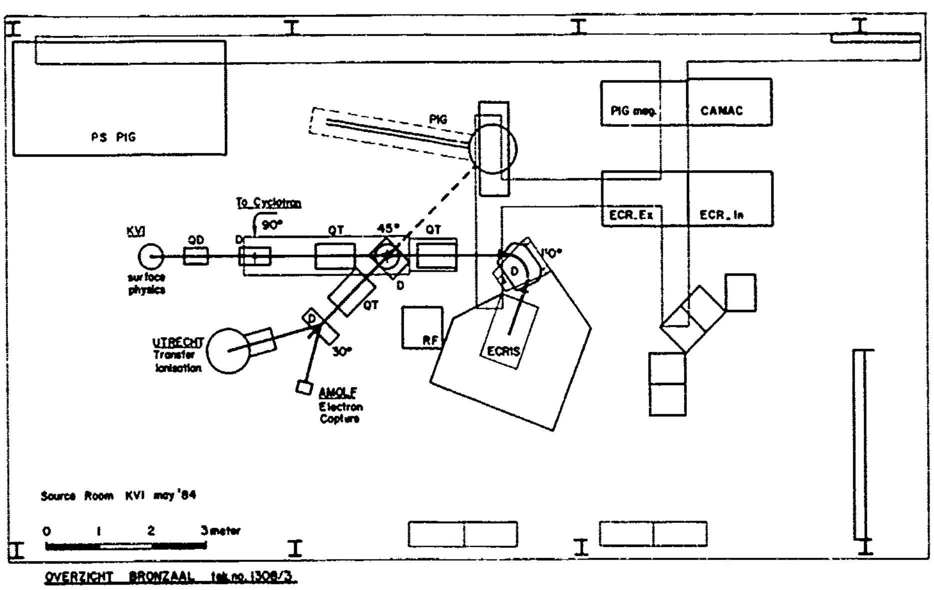
ii) A collision chamber for triple coincidence measurements of transfer ionisation processes, constructed by A. Niehaus and M. Mack of the University of Utrecht and connected to the ECR in May 1984.

iii) A collision chamber for surface physics experiments, equipped with a solid (presently tungsten) target manipulator and an electrostatic analyser. This set-up was constructed by A. Boers, J. Eilander and S. de Zwart of the University of Groningen, presently at KVI, and connected early this year.

Later this year the source area will be expanded; a second surface physics set-up will be connected and a position for a temporary set-up of other users will become available.

Presently ion beams in the energy range (2-20) × q keV are used with reasonable transmission, which decreases of course with decreasing energy. In order to reach the interesting region of smaller velocities we will try to use 5 kV beams with deceleration in the collision chamber.

From the great variety of beams used in the AMOLF chamber we quote here: 45 nA C^{6+}, 450 nA O^{7+}, 13 nA O^{8+}, 22 nA Ne^{9+}, all at 12 kV.



THEORY AND EXPERIMENT OF ELECTRON CAPTURE IN COLLISIONS OF MULTIPLY CHARGED PROJECTILES WITH LIGHT TARGETS

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In a joint theoretical[1] and experimental[2] effort, we have examined in detail the capture channel in collisions of multiply charged projectiles with light targets. Comparison of theoretical and experimental cross sections have shown the inadequacy of the first and second Born cross sections to describe the capture process. On the other hand, the multiple scattering approaches implemented by Dubé[1] were in much closer agreement with the experimental data, indicating the importance of higher order contributions to the electron transfer collision.

We report new high-resolution photon-spectroscopic results[3] of electron capture of energetic (2-5 MeV) C^{4+} ions with H_2 and He, from which we extract specific (n,l) capture cross sections. The present study extends our previous work and demc strates anew the superiority of the multiple scattering theories, in particular that of the Continuum Distorted Wave (CDW) calculations. The multiple scattering effects are also seen to be important not only for the absolute magnitudes but also for the relative population of the final states. As further refinement of the theoretical approaches, we also discuss the influence of the linear Stark effect on the final state distributions.[4]

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ATOMIC-EXPANSION STUDIES OF CHARGE TRANSFER IN ION-ATOM COLLISIONS

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In the recent past, much progress has been achieved in the efficient and accurate theoretical description of capture processes in (quasi-)one-electron atomic collisions under conditions where the very number of competing physical channels precludes an understanding by simple models. Such conditions arise when highly charged ions collide with neutral atoms and capture occurs into excited projectile states. In a standard procedure, the time-dependent electronic wavefunction is decomposed into a set of either travelling atomic orbitals (AO) or travelling molecular orbitals (MO).[1] With ever inceasing basis sets for proper representation of the important physical channels, the semiclassical coupled equations, i.e. the equivalent of the Schrödinger equation within the basis, have been solved, and total as well as partial transfer cross sections have been calculated over generally two orders of magnitude of collision energies around the transfer maximum. In this communication, we present and discuss results derived with AO expansions which are particularly suited for investigations of the systems under consideration. Firstly, in distant collisions, they are the natural choice of basis sets, being equivalent to MO expansions there even in slow collisions. Secondly, they can easily be modified for use in close collisions by introducing pseudostates in the form of united-atom orbitals. Finally, their use is techniqually more convenient and less susceptible to errors than is the use of large-size MO expansions.[1]

We have studied a number of collision systems at energies 0.1-20 keV/amu, and details will be shown at the Conference. We summarise the results in the following points.

(A) Z^{Z+}+H collisions, Z=2-8. Generally, calculated total transfer cross sections agree with results from other large-scale close-coupling studies where available. Discrepancies, however, between calculated partial transfer cross sections for non-dominant channels are reflected, in the case of O^{8+}+H collisions, even in calculated total transfer[2].

(B) A^{q+}+Li(2s) collisions, A^{q+}=H^+, He^{2+}, C^{4+}. One-electron potential models are applied to these systems. Results for H^+ and He^{2+}, while controversial at the time of publication, have been confirmed in recent experiments, see, e.g. ref.3. In figure 1, calculated partial transfer into the n=5 shell (full symbols) is compared with preliminary experimental data[4] (open symbols) for C^{4+}+Li. Qualitative agreement is observed for all l-transitions other than for l=3. The reason for the latter deviation as well as some deviation by a constant factor between calculated and measured total transfer cross sections is not understood yet.

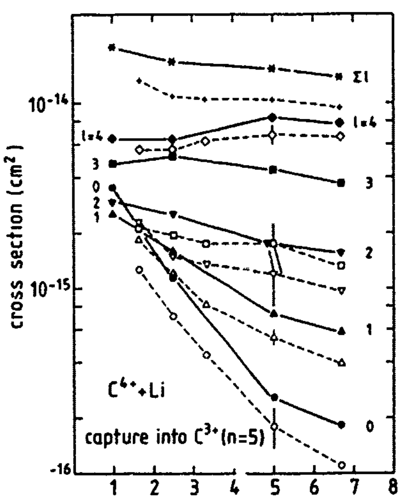

Fig.1: n=5 partial transfer in C^{4+}+Li collisions.

This work is supported in part by the US Department of Energy.

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U^{87+} - U^{92+} PRODUCED AT RELATIVISTIC ENERGIES

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Charge state distributions of 200 MeV/nucleon, 437 MeV/nucleon and 962 MeV/nucleon uranium, obtained from the Lawrence Berkeley Laboratory's Bevalac, have been measured for targets from carbon (Z = 6) to gold (Z = 79). At 962 MeV/nucleon, a 150 mg/cm^2 copper target produces a distribution of roughly 85% bare U^{92+} and 15% hydrogenlike U^{91+}. At 200 MeV/nucleon large fractions of heliumlike and hydrogenlike uranium (Fig. 1) are observed.

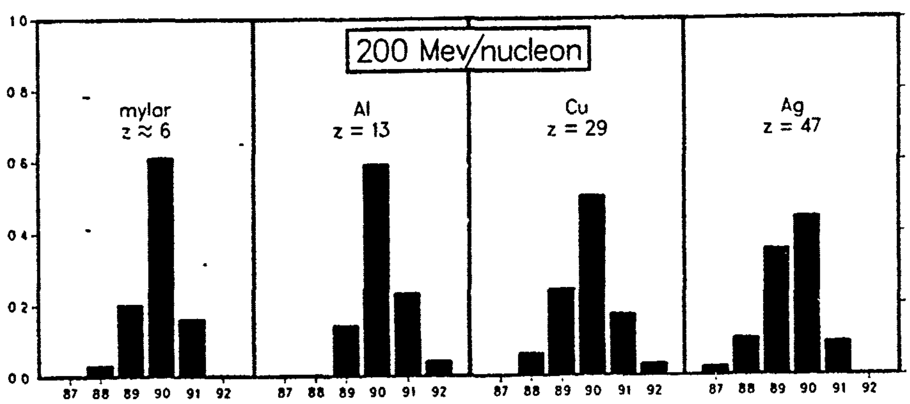

Figure 1. Fractions of U^{87+} - U^{92+} observed by passing 200 MeV/nucleon uranium through equilibrium-thickness targets.

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ELECTRON CAPTURE FROM ATOMIC HYDROGEN IN THE KEV/AMU ENERGY RANGE

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Molecular calculations including translation factors of the form proposed by Errea et al.[1] have been carried out for electron capture from atomic hydrogen by fully stripped ions with charges between 5 and 10 as well as for $O^{6+}(1s^2)$, $N^{5+}(1s^2)$ and $C^{4+}(1s^2)$ impact. The impact energy range is 0.25-25 keV/amu.

1 - Fully stripped projectiles :

Our calculations are in good agreement with those of Gren et al.[2], Fritsch and Lin [3] and Lüdde and Dreizler [4]. However, noticeable discrepancies can be observed with the multichannel Landau-Zener method of Janev et al.[5]. The differencce is particularly large for transitions that occur at large internuclear distances R (R > 10 a.u.). For example, in the case of $F^{9+}-H$, the population of the final state $n=7$ of F^{8+} is two orders of magnitude larger in our calculation. This can be explained by a break down of the Landau-Zener approximation which should be replaced by the Nikitin-Dremkov exponential model for such transitions [6].

The variation with projectile charge of our results is in good agreement with that obtained with new experimental results obtained in Grenoble with the ECR source by Bliman et al. Oscillations only exist for energies lower than 1 keV/amu. As a consequence a number of earlier experimental results showing oscillations should be related to target or projectile electronic structure.

2 - Projectiles with a $(1s)^2$ core :

We have used a model potential approach. Agreement is obtained within 20 % with the calculations of Olson et al. [7] based on a configuration-interaction approach. Our results confirm the role of rotational coupling to π states as for the case of fully stripped ions.

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SINGLE ELECTRON CAPTURE IN SLOW He^{2+} - Li COLLISIONS

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We have extended previous measurements of our group[1] on one-electron capture in He^{2+} - Li collisions towards lower velocities. With a He^{2+} beam produced by an ECR ion source we were able to cover the velocity range 0.15 - 0.6 a.u. The ion beam was crossed with a thermal beam of Li atoms from an oven operating under effusive flow conditions. The Li target thickness was determined via measurement of the LiI(2p→1s) transition, excited by electron impact.

Cross sections for emission of the np → 1s (n=2,3,4) Lyman series in HeII have been measured with an absolutely calibrated VUV grazing incidence monochromator. From these we have deduced the total capture cross section σ_t and the subshell-selective cross sections σ_{3p} and σ_{4p}.

Correction factors connected with the polarisation of the emitted radiation were applied to our data, using theoretical results of Fritsch and Lin[2], who give capture cross sections for nlm-states.

Our data are compared with calculations by several authors[2,3,4,5,6] that show diverging results towards low velocities. As an example the comparison for σ_t is shown in the figure.

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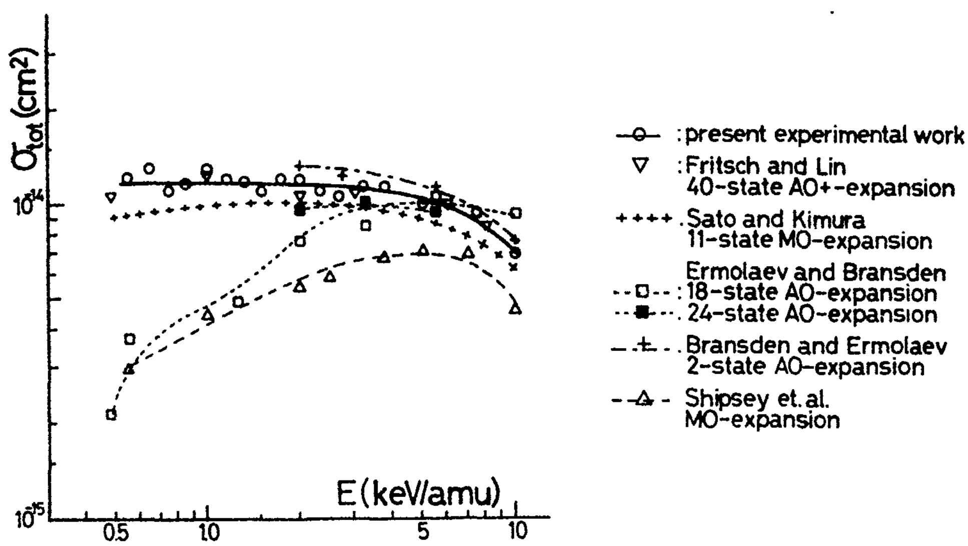

LIFETIMES OF DOUBLY EXCITED QUARTET STATES IN THE THREE-ELECTRON-SYSTEMS OF MG^{9+} AND AL^{10+}

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The $1s2s2p\ ^4P^o$ and $1s2p^2\ ^4P$ states form the lowest-lying high-spin multiplets in doubly excited three-electron ions. Spin-orbit ($\sim Z^4$), spin-other-orbit ($\sim Z^3$) and spin-spin ($\sim Z^3$) interactions contribute to the finestructure splittings of these states. The multiplet separation $^4P^o-^4P$ increases approximately proportionally to Z. Studies of the finestructure therefore ought to be aimed at the ion with the highest possible nuclear charge. The ^4P states, however, may decay not only via the $^4P^o-^4P$ UV branch but also by x-ray decay to doublet levels or by autoionization. The importance of the latter processes increases with the nuclear charge. Thus the UV branch is considerably weakened and the lifetimes of the upper levels are shortened. Our data on $_{12}$Mg and $_{13}$Al are those for the highest Z up to now.

EUV spectra of foil-excited Mg and Al ions have been recorded using a 2.2 m McPherson 247 grazing-incidence-monochromator. The transitions between the $^4P^o$ and ^4P multiplets have been identified[1,2]. A comparison of finestructure intervals and multiplet separation with recent theoretical data shows good agreement with calculations by Hata and Grant[3].

For the purpose of measuring decay curves of the extremely weak VUV transitions a new spectrometer - designed for high speed - has been built, which is equipped with a 550 l/mm torodial grating (for reduced astigmatism at the cost of spectral resolution). A temporal resolution of 2 ps has been achieved. The lifetimes under study are in the range of 4-170 ps. Comparison of experimental and theoretical data shows good agreement with calculations by Chen, Crasemann and Mark[4] as well as with other experimental data[5,6] which are available only for the $2\ ^4P_{1/2}$ level.

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ENERGIES AND OSCILLATOR STRENGTHS FOR ALLOWED TRANSITIONS IN S V, Cl VI AND Fe XV

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Experimental energy levels for many states of S V have recently been published[1], and similar work on Cl VI is in preparation[2]. Experimental work on Fe XV is much more fragmentary[3].

We have performed configuration interaction calculations for these three ions. All the n = 3 states have been included, together with many of the $3\ell 4\ell'$ states. Both singlet and triplet states are considered, thus extending the work of Froese Fischer and Godefroid[4]. Calculated energy levels for S V and Cl VI agree well with experiment (except in a small number of cases where we suggest a reassignment). Many new energy levels are predicted for Fe XV.

The calculations in S V and Cl VI are entirely in L-S coupling. For Fe XV, we have also included the mass-correction and Darwin operators which, though spin-independent, are important in obtaining reliable splittings between the energies of different multiplets. The oscillator strengths of transitions between all states included have also been obtained.

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ELECTRON CAPTURE BY STATE-SELECTED MULTIPLY CHARGED IONS

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As shown in different experiments[1,2], electron capture by multiply charged ions may depend strongly on the internal state of the projectile. Therefore we developed a method, which allows the study of capture reactions with state-selected primary ions (demonstrated for Ar^{2+} ions). The apparatus is shown in Fig. 1.

In collision chamber I different excited states of Ar^{2+*} ions are produced by electron capture in Ar^{3+}/Ar collisions. By aid of a magnetic sector field and the energy monochromator Ar^{2+} ions in a specific state are selected and used as new projectiles in collision chamber II.

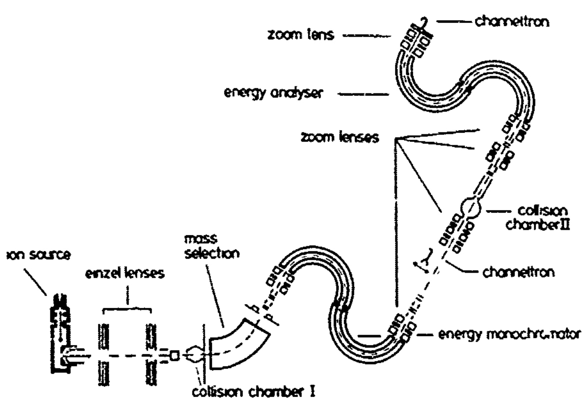

Fig. 1 Schematic drawing of the experimental setup

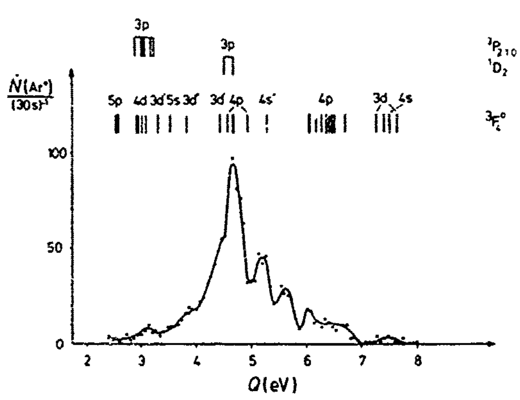

Fig. 2 Ar^+ translational spectrum formed in $Ar^{2+}(^3F_4^o)/He$ collisions ($E = 607$ eV; $\Theta = 0^o$)

Fig. 2 shows the translational spectrum of Ar^+ ions produced by electron capture of Ar^{2+} (in the highly excited metastable $(3d'\,^3F_4^o)$ state) in He. Advantages of this method as well as further experimental possibilities are: 1. Improvement of the energy resolution, 2. Easier identification of reaction channels by secondary reactions, 3. Information on life times and branching ratios of excited states, 4. Production and detection of highly excited metastable states.

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ENERGY-GAIN SPECTROSCOPY BY MULTIPLY CHARGED RECOIL IONS

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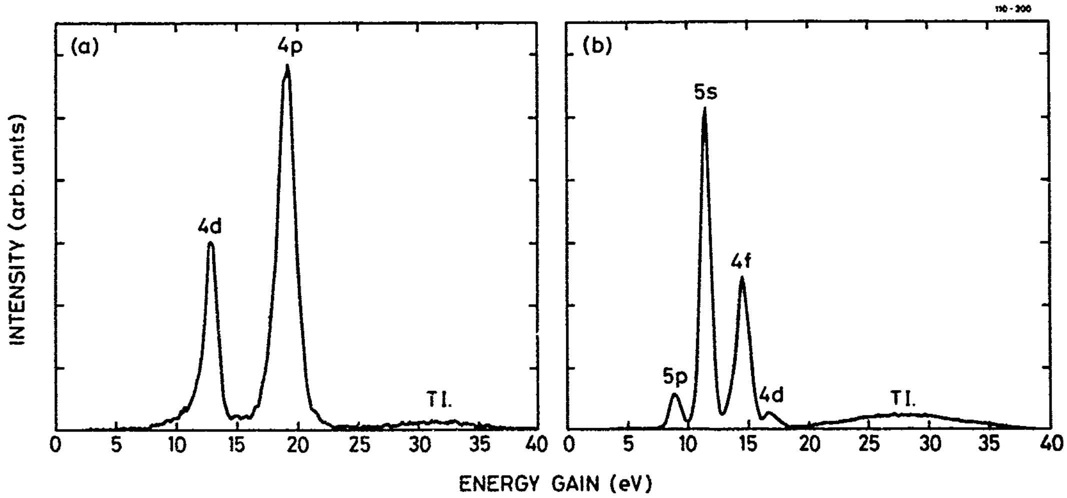
In recent years, determination of final-state population in electron-capture collisions between highly charged ions and atoms has attracted much attention [1]. One way to obtain experimentally such information is to perform energy-gain spectroscopy measurements on the projectiles after a capture collision. We have used this method to investigate electron capture for Ar^{q+} ions $2 \leq q \leq 10$ in the energy range from 100 eV to 2 keV.

In the figure are shown energy-gain spectra obtained for the following collision systems,

$$Ar^{6+} + Ne \rightarrow Ar^{5+}(n,\ell) + Ne^{+} + Q ,$$

$$Ar^{6+} + Ar \rightarrow Ar^{5+}(n,\ell) + Ar^{+} + Q ,$$

where Q is the internal energy defect in the collision. The energy-gain ΔE of the Projectile Ar^{q+} ion is approximately equal to Q for small scattering angles and small relative energy changes. As can be seen from the figure, the energy resolution is sufficient to resolve the various excited states for many-collision systems.



The present setup is consid[illegible] [illegible] first-generation experimental approach. When the CRYEB[illegible] [illegible] source in Stockholm is operational (1984/85), it is pla[illegible] [illegible]o continue this type of experiments with even more highl[illegible] [illegible]d ions.

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EXPERIMENTAL RESULTS FROM AN ECR SOURCE USING AN OCTUPOLE

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The large superconducting ECR source, Ecrevis (Louvain-laNeuve) has shown better charge state distribution (CSD) than smaller sources like minimafios or the Berkeley source. Computer simulation indicates that the reason could be a lower average electron energy in the smaller sources. It has been suggested by Jongen that the size of the magnetic gradients in the source could be the energy limiting factor, and that the average electron energy could be increased by replacing the usual sextupole by an octupole. After an extensive series of tests, the sextupole of the Berkeley source was replaced by an octupole. After modification, the CSD have been substantially improved in the direction of higher charge states, with a substantial reduction of low charge state intensity. The intensity of higher charge states like argon 14+ or krypton 18+ increased by one order of magnitude. The new CSD are now very similar to those of the large Ecrevis source, indicating a probable gain in average electron energy.

PROPOSAL FOR A TOTALLY SLIT-LESS MONOCHROMATOR FOR USE WITH THE BEAM-FOIL SOURCE

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In a Fastie-Ebert or Czerny-Turner monochromator used with a photomultiplier as detector, the entrance and exit slits are normally of equal spectral width and either may be regarded as the field stop of the instrument; also, the diffraction grating acts as the aperture stop. It is proposed to remove both entrance and exit slits and to use condensing optics such that the grating acts as the *field* stop; also a camera lens in the Doppler-matched[1,2] condensing system acts as the aperture stop. The photomultiplier is replaced by an imaging photon detector[3].

The resulting instument has a uniquely high value of resolvance-throughput product[4], less effective detector noise and other advantages, making it suitable for studies of spectra. An anamorphotic version is suitable for measurements of decay curves.

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EXPERIMENTAL OSCILLATOR STRENGTHS FOR LEVELS OF TIN IONS IN THE AgI AND CdI ISOELECTRONIC SEQUENCES[1].

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J.L. Bahr
Department of Physics, University of Otago, Dunedin, New Zealand

We have used a Field Emission Ion Source (Oxford Applied Research) in a 2 MV Van de Graaf to obtain 2μa beams of Sn^+ ions, with energies between 0.7 and 1.5 MeV. By conventional beam foil spectroscopy we have obtained spectra and mean lives for lines and levels in SnIII, SnIV and SnV. We compare our experimental oscillator strengths with recent theoretical calculations for levels in the AgI and CdI isoelectronic sequences.

[1] Work supported by the Province of Alberta and the Natural Sciences and Engineering Research Council of Canada.

THE ORNL ECR MULTICHARGED ION SOURCE

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A multicharged ion source based on Electron Cyclotron Resonance (ECR) heating has been designed and built at ORNL. The ECR ion source is expected to produce higher charge states and higher beam intensities than the present ORNL PIG multicharged ion source, and will thus permit study of collision processes involving ions of higher charge states in experiments requiring higher beam intensities than can presently be obtained. The ion source, shown schematically in Fig. 1, is a two stage design, the first stage producing a cold, high density plasma, while the second stage strips the ions as they diffuse through a magnetically confined plasma containing fast electrons that are ECR heated. Electron confinement is provided by a minimum B configuration produced by the superposition of an axial mirror field (mirror ratio of ≈2), shown in Fig. 2, and a radial hexapole field.

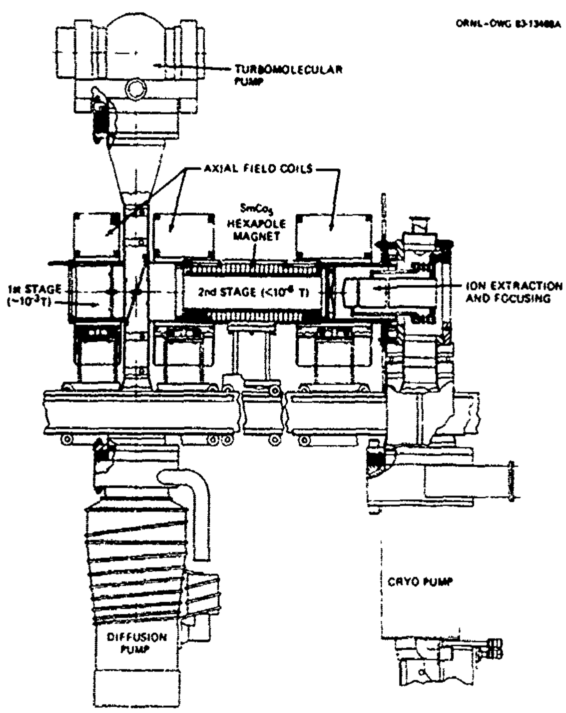

Fig. 1. The ORNL ECR multicharged ion source.

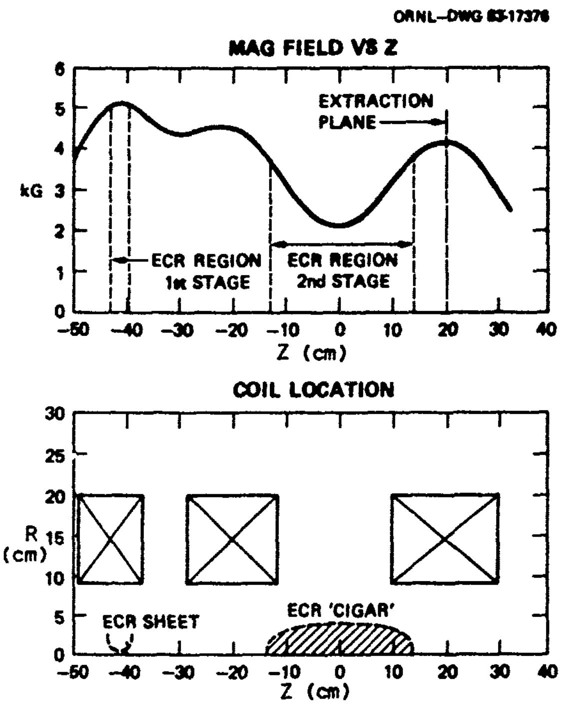

Fig. 2. Solenoidal magnetic field on axis vs. axial position; location of solenoidal coils and ECR regions.

Results of initial performance tests of the ECR ion source at 2.45 GHz will be presented. Operation of the ion source at the design frequency of 10.6 GHz awaits delivery of the 10.6 GHz microwave generator, scheduled for July 1984. The first experiments planned for the new source will be measurements of total electron capture cross sections for fully-stripped projectiles incident on atomic hydrogen at energies below 1 keV/amu.

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*Operated by Martin Marietta Energy Systems, Inc., for the U.S. Department of Energy under Contract No. DE-AC05-84OR21400.

BEAM-FOIL INTERACTION OF HIGHLY IONIZED CHLORINE ION AT HIGH ENERGY REGION

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To get information on the correlation between the multiple scattering and charge state as a function of foil thickness, measurements have been performed for 150 MeV incident Cl^{10+} ions with a two-dimentional position sensitive detector.

Fig. 1 shows the integrated charge-state distributions of Cl ions emerging from 2.5 to 180 $\mu g/cm^2$ carbon foils following impact of 150 MeV Cl^{10+} ions. The distribution for the foils of 2 and 8 $\mu g/cm^2$ in thickness displays characteristic nonequilibrium behavior. Average charge shifts to the multivalent with increasing the foil thickness and is almost 15-valent for the foils thicker than 50 $\mu g/cm^2$, which reflects the multiple scattering. The form of each distribution is a simple Gaussian for lower charges but that for the charges of 16 and 17 valences deviates from the Gaussian distribution due to large binding energy of s electrons.

In Fig. 2 is represented the charge dependence of the half angle of scattering($\theta_{1/2}$) of the peak for the various thickness of foils as parameters. The angular spread shows a tendency to increase with increasing charge state of exiting ions. The increase above charge fraction of 15 is remarkable owing to the greater binding energy of K-shell electrons compared to L-shell ones, which is consistent with the experimental findings as shown in Fig. 1 for the charge state distributions. One striking feature is a remarkable broadening of Cl^{16+} ion for the thinnest foil of 2.5 $\mu g/cm^2$.

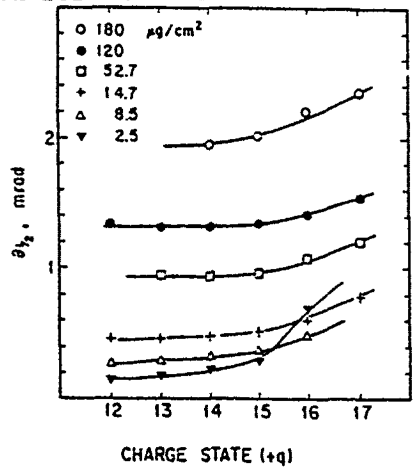

Fig. 2.

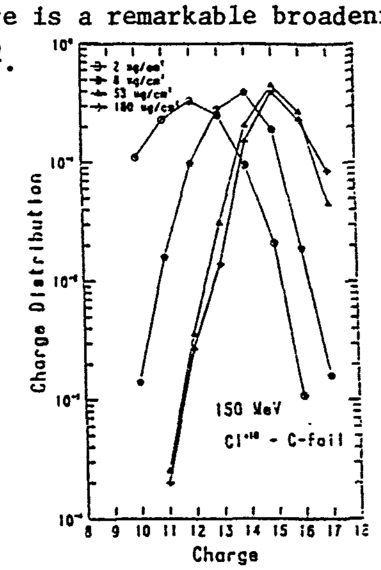

Fig. 1.

TRANSFER IONISATION WITH BARE 100 keV Ne^{10+} IONS

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We have measured charge state distributions of recoil ions B^{i+} produced in transfer-ionization reactions of Ne^{10+} ions colliding with rare gas atoms B = He, Ne, Ar, Kr, Xe at 100 keV impact energy:

$$Ne^{10+} + B \rightarrow Ne^{9+} + B^{i+} + (i-1)\cdot e$$

For the targets B = Ne, Ar, Xe also the two-electron-capture reactions $Ne^{10+} \rightarrow Ne^{8+}$ were studied.

The measurements were performed by means of a crossed-beam coincidence time-of-flight technique[1]. A collimated beam of Ne^{10+} ions produced by the Grenoble ECR-ion-source intersects at an angle of 90° a thin gas target jet. The charge state distribution of target recoil ions B^{i+} is determined from their flight times to a channeltron detector.

For the single-electron-capture reactions recoil ion charge states up to He^{2+}, Ne^{3+}, Ar^{4+}, Kr^{4+} and Xe^{5+} have been detected. The highest charge states produced in the two-electron-capture reactions were Ne^{5+}, Ar^{7+} and Xe^{9+}. The observed charge-state distributions are compared to the predictions of a statistical model for transfer ionization[2] and to theoretical calculations.

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AUGER SPECTROSCOPY OF MULTIPLY IONIZED Ar ATOMS AFTER 500-keV Ar^{+}+ Ar COLLISIONS

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In collisions of 500-keV Ar^{+} ions with Ar atoms, L shell excitation and ionization of M electrons occurs[1]. After the collision, these highly excited and ionized atoms decay predominantly by emission of Auger electrons. The energy of the emitted Ar-L Auger electron depends on the number of M shell vacancies. Therefore, the Ar-L Auger spectrum yields information about different charge states produced in 500-keV Ar^{+}+Ar collisions.

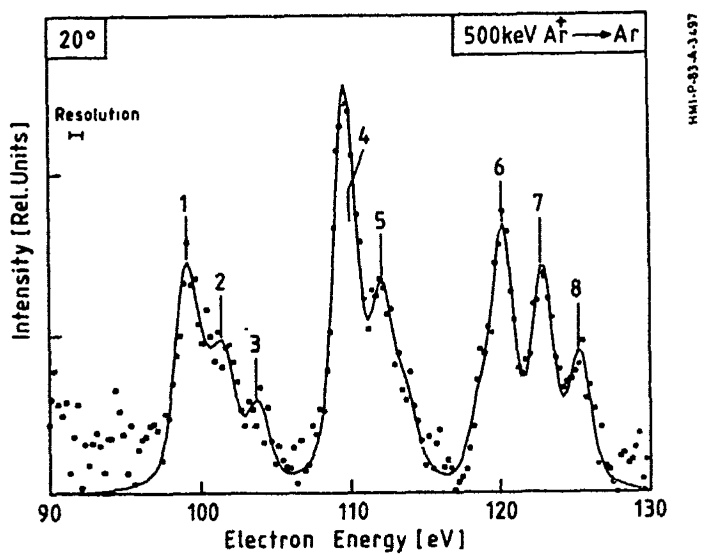

Fig.1: Highly resolved Ar-L Auger spectrum

A highly resolved Auger spectrum after background subtraction is shown in Fig.1. The spectrum was measured with a parallel-plate analyser[2]. The low energy group (labelled 1,2 and 3) belongs to the sodium-like configuration[3] $1s^2 2s^2 2p^5 3s^2$ (Ar^{7+}). For the production of this configuration all 3p electrons have to be removed in a single collision.

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CORE-DEPENDENT ELECTRON CAPTURE INTO EXCITED SUBSHELLS OF FAST HIGHLY IONISED Sm-PROJECTILES

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The charge exchange of fast highly ionised atoms is dominated by the capture of one or two electrons at single collision conditions. The capture into excited subshells of the projectile is essentially followed by decay via cascades and may be spectroscopied by the emitted x rays. The M- and L- x-ray emission of F- and O-like Sm projectiles at the end of those cascades were measured under single collision conditions ($Sm^{q+} \rightarrow$ He, Ar, Xe at 3.6-4.8 MeV/u, q = 53+, 54+).

At a fixed charge state the incoming projectile may be found in various metastable states, which include different total angular momenta J_i. For instance at two incoming L-vacancies (Sm^{54+}) with both the vacancies in the L_3-shell the angular momenta are $J_i = 0,2$, while for one vacancy in the L_3 shell and the other one in the L_2-shell $J_i = 1,2$ results. These incoming projectiles act as cores for a captured electron. The emitted x-ray spectra depend in a two-fold way on these core angular momenta. Firstly each core has its own distribution of capture into excited subshells. Secondly the angular momenta J_f after capture force a partial metastability of the emitted x rays. Therefore not all of the emitted x rays along the beam line can be registered by the x-ray detector because of the high projectile velocity.

Together with calculations of the relativistic transition probabilities and transition energies[1] it was possible to consider these features by simulating the x-ray spectrum after capture of one electron into a given excited subshell. This includes also higher multipole orders of x ray emission (E1, M1, E2, M2).
The interpretation of a measured spectrum is given by a suited superposition of simulated spectra. From this procedure we get the capture cross sections of the excited subshells.

1. Das, priv. comm. and I.P. Grant et al., to be published

ELECTRON CAPTURE INTO VARIOUS ANGULAR-MOMENTUM STATES IN COLLISIONS BETWEEN HIGHLY CHARGED, MEDIUM-VELOCITY Au^{q+} AND H_2

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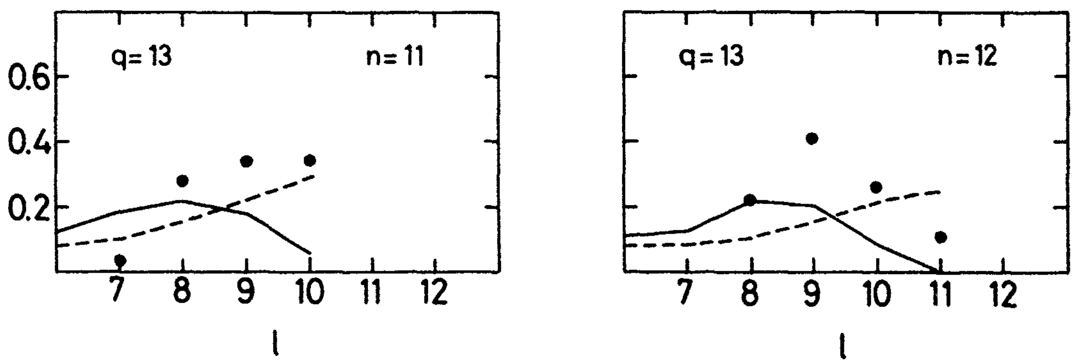
Information on state-selective electron capture in collisions between highly charged ions and atoms is obtained through detection of the subsequent radiation. We have earlier [1] measured emitted light from the collision system $Au^{q+} + H_2$ at 20 MeV for charge states q from 12 to 18 and obtained information on capture into various n states.

To measure the population of the various ℓ states, it is necessary to improve the spectroscopic resolution drastically to better than ~2 Å. This resolution is obtained by applying the so-called refocussing technique [2], where the Doppler variation in wavelength is matched to the reciprocal linear dispersion of the spectrometer so as to eliminate the Doppler broadening to first order.

The capture cross section to different n,ℓ states is obtained by measuring the radiation emitted in the subsequent transitions and correcting for branching ratios and cascades.



In the figure are shown the relative ℓ cross sections in the cases Au^{13+} + e: n=11 and n=12, measured and compared with theoretical predictions [3]: CTMC [4] —— and UDWA [5] ---. Similar results are obtained in the cases Au^{12+}+e: n=11; Au^{14+}+e: n=11,12; Au^{15+}+e: n=11,12,13.

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MULTIPLE IONIZATION OF ATOMS BY HIGHLY IONIZED HEAVY ION IMPACT

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We have measured the charge distribution of slow Ar^{i+} ions recoiled in 1.05 MeV/amu Ar^{q+} (q=4 - 14) ion impact. When the L-shell vacancies are brought into collision, the drastic change in the charge distribution has been observed. The observed charge distribution is analysed in terms of the ionization probability based on the independent electron model. The probability $P_{m+\ell}$ for ionizing m electrons in the M-shell and simultaneously ℓ electrons in the L-shell among 8 electrons in each shell of Ar atom, corresponding to $i=m+\ell$, is given as follows :

$$P_{m+\ell} = \binom{8}{m} p_M^m (1-p_M)^{8-m} \binom{8}{\ell} p_L^{\ell} (1-p_L)^{8-\ell}$$

where p_M and p_L represent the ionization probabilities of a single electron in the M- and L-shells, respectively. As far as the ionization of slow ions with $i \geq 9$ is concerned, it can be assumed that p_M is constant. Then, the relative ionization probability is represented by only p_L. By comparing the observed charge distribution with the independent electron model, the ionization probability for production of Ar^{i+} ions could be determined as shown in Fig.1. The probability p_L in impact of Ar ions with q=4 through 6 is found to be constant, whereas it increases singnificantly for ion with q=10 through 14. By interpolating these results, we can conclude that the ionization is enhanced once the incident ions bring the L-shell vacancies into collision. This enhancement is believed to be due to the electron transfer of target atoms into the L-shell vacancies of projectiles, as reported in X-ray and Auger electron yield.

Combining these charge distribution data with the absolute values of total ionization cross sections determined through condenser plate measurements, we also determined the absolute partial cross sections for production of multiply charged Ar^{i+} ions. These total and partial ionization cross sections are compared with similar data previously reported. The measurements are being extended to other ion-atom combinations .

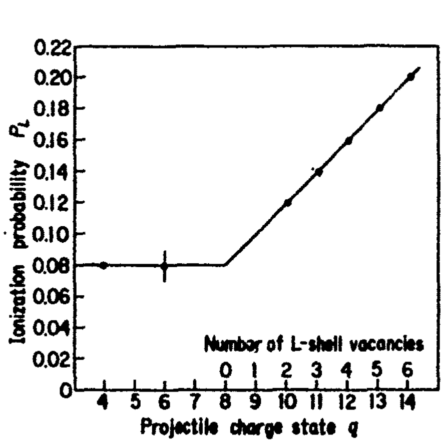

Fig.1

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ONE ELECTRON CAPTURE PROCESSES OF VERY HIGHLY IONIZED I^{q+} ($q\leq 41$) IONS IN COLLISIONS WITH He ATOMS AT LOW ENERGIES

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We have recently engaged in systematic investigation of one-electron capture processes of highly ionized heavy ions in collisions with He atoms at low energies and reported some results on B, C, N, O, F and Ne ions including the naked ions[1] and on Kr^{q+} ($q\leq 25$)[2] ions. The present work is an extension of these works toward very highly ionized ions. The observed cross sections for I^{q+} ions are found to change little with the collision energy over 0.75xq to 3xq keV. In Fig.1 are shown the measured total one-electron capture cross sections for Kr^{q+} and I^{q+} ions at around 200 eV/amu impact energy. Note that the cross sections can be represented as a function of the charge q, irrespective of ions. These results are summarized as follows :

For low q ($q<10$) ions including the naked light ions and less ionized heavy ions, the cross sections are found oscillatory when plotted a a function of the ion charge q and show a maximum when plotted as a function of the crossing radius of potential energy curves in quasi-molecules where the electron transfer takes place during collision.

On the other hand, for high q ($q\geq 10$) ions, the situation is changed. The oscillation of the cross sections disappears and the cross sections increase monotonically with increasing the charge of ions q and gather on a single empirical curve. The cross sections reach 10^{-14} cm^2 for ions with q = 35. Furthermore, it is noted that the cross sections increase roughly with the square of the crossing radius for ions with q up to 38.

These results are analysed using the Landau-Zener model. The present analysis clearly indicates that the Landau-Zener model can reproduce quite well the observed results for these ions with very high charge state at low energies.

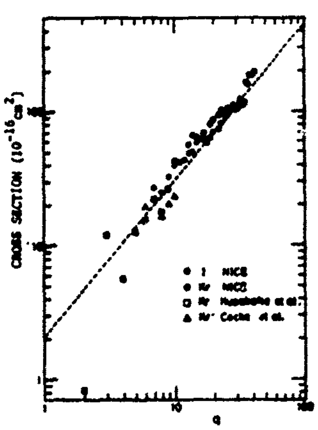

Fig.1

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A SEMICLASSICAL ANALYSIS OF ORBITING RESONANCES IN SLOW CHARGE TRANSFER PROCESSES

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We present a systematic study of the orbiting non-radiative charge transfer mechanism in a realistic two-state (crossing) model.

The angle-integrated cross sections are obtained within the partial wave formulation using certain phase integral expressions for the S matrix elements. Special emphasis is made to explore the energy dependence of the charge transfer cross sections. To test the reliability of the computations we compare our results for the process $N^{3+}(1s^2 2s^2)^1S + H(1s) \rightarrow N^{2+}(1s^2 2s^2 3s)^2S + H^+$ with an exact method[1].

Two different orbiting energy regions are observed: $E = E_{ex} < E_{min}$ and $E = E_{int} > E_{min}$. In the external orbiting energy region ($E = E_{ex}$) a quasimolecule can be formed with an orbiting radius exceeding the level crossing distance. The presence of such a large quasimolecular formation generally increases the reaction cross section and prominent resonance spikes can be observed. The notion of a vibrational quantum number associated with this type of resonance is not unique since the quasimolecule vibrates with a certain probability along one diabatic and one adiabatic energy well depending on the coupling strength near the crossing point. In the internal orbiting energy region ($E = E_{int}$) a small quasimolecule with orbiting radius less than the crossing distance can be formed. This mechanism does not in general increase the cross section but produces a characteristic mixed resonance structure with positive as well as negative spikes.

The external and internal orbiting regions are separated by an energy gap, the width of which depends on the coupling strength, where the orbiting charge transfer mechanism is particularly inefficient. In the reaction cross section this energy gap shows up as a pronounced minimum ($E = E_{min}$) in the gross structure.

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He^{+} (np) CROSS SECTIONS FOR 2,3,4 AND 5 MeV C^{4+} IONS COLLIDING WITH He ATOMS

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Simultaneous excitation and ionization of atomic He by energetic C^{4+} ions has been studied both experimentally and theoretically. Relative cross sections for He^{+} (np) production by $C^{4+} \rightarrow He$ impact under single collision conditions were measured by means of high resolution EUV spectroscopy. Thus photon emission from the HeII (np → 1s) Rydberg series was detected using a 2.2 m grating incidence spectrometer under 90° to the ion beam direction. In the EUV spectra transitions from HeII (np) initial states up to n = 8 were clearly resolved. Different cascade feeding mechanism which may enhance the population of HeII (np) states are discussed. Experimental cross sections are compared with theoretical calculations.

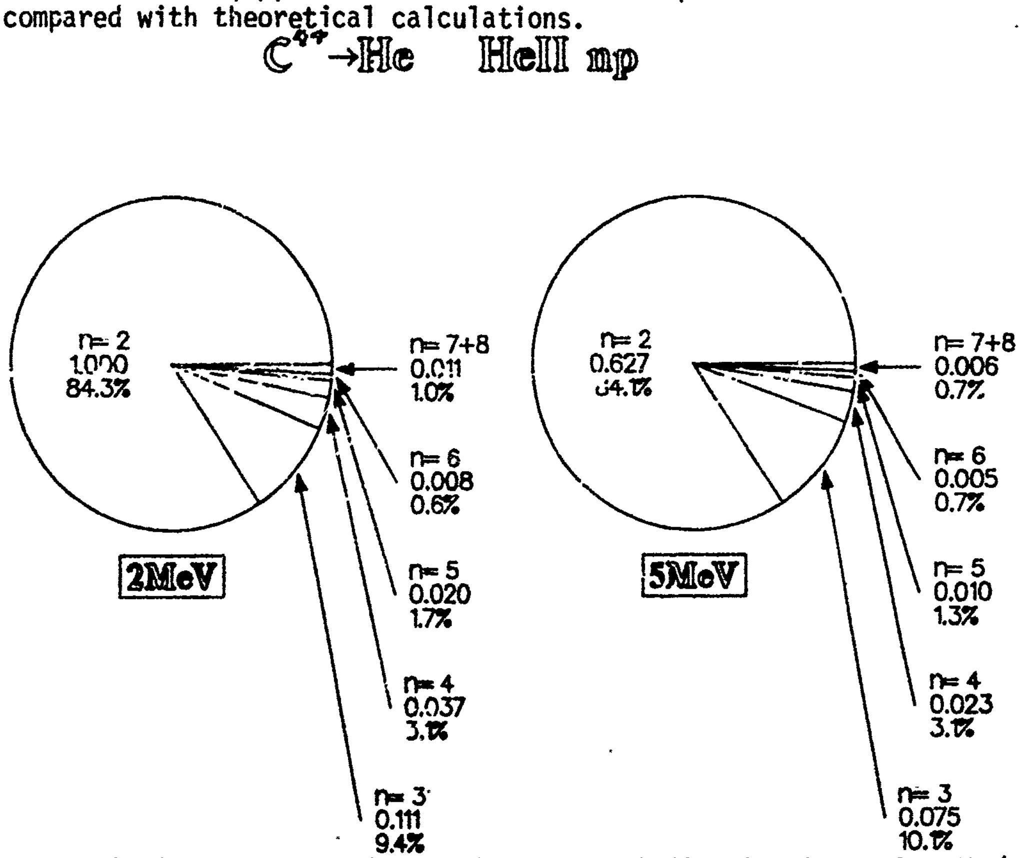

Fig. 1. Relative cross sections and percentual distributions of HeII (np) states.

IDENTIFICATION OF NE I-LIKE TRANSITIONS IN THE VUV SPECTRUM OF FOIL-EXCITED TITANIUM

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The VUV spectrum of foil-excited titanium has recently been recorded[1]. Although most of the lines in the spectrum could be identified with lines known to belong to charge states Ti^{q+} (q=8-11,13,14) a number of fairly strong lines eluded identification with known transitions. Obviously the spectrum of Ne I-like Ti^{12+} is missing in the available experimental data to compare with. Ne I-like Ti^{12+} features 36 states with principal quantum number n=3. Most of the transitions between these states contribute to the spectrum in the range of interest (λ=28-56 nm).

Starting from various theoretical data[2-4] on the term structure we have simulated spectra taking transition energies and transition probabilities into account as well as the time resolution of the beam-foil spectroscopic method and the detection efficiency variation of the monochromator/detector used[5]. By a trial-and-error variation of the term structure about 30 of the most prominent n=3, Δn=0 lines have been matched with observed spectral features. The term structure derived from the data is compatible with an extrapolation of the systematic trends observed in the Ne I-sequence up to Ar IX[6] and is close to the structure predicted by Bureeva and Safronova[3] and by Fawcett[4].

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Beam-Foil study of $2p^43s$, 3p and 3d configurations of S VIII

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Abstract

The spectrum of seven times ionised sulphur, S VIII, has been observed from 460 to 1150 Å. About forty lines have been identified as combinations between 43 levels of $2p^22p^43s$, 3p and 3d configurations. The 3p levels have been located. The experimental results are supported by parametric calculations and isoelectronic comparations.

STUDY OF THE BEAM-FOIL EXCITATION MECHANISM WITH THE USE OF SULFUR AND CHLORINE PROJECTILES

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The relative level population has been measured for beam-foil excited S VI at 3 MeV and Cl VII at 5.5 MeV. For S VI, the level population is fairly independent of the principal quantum number n, whereas a pronounced maximum is found for levels with n = 8 in Cl VII.

A two-step model has been applied to calculate theoretical values for the relative level populations. Satisfyingly good agreement is found between experiment and theory. The results confirm the previously proposed idea that final projectile levels whose binding energies are comparable to or smaller than the binding energies for electrons in the valence band of the foil, are mainly populated from pickup of electrons from the valence band of the foil, when the projectile leaves the back of the foil.

STUDY OF MOLECULAR BEAM-FOIL EFFECTS WITH THE USE OF CN PROJECTILES

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Singly ionized CN radicals have been accelerated to 3 MeV in a Pelletron tandem accelerator. The projectiles passed through an exciter foil with or without a pre-stripper foil inserted 5 cm upstream from the exciter foil. An optical monochromator with detector observed photons emitted downstream from the exciter foil. For some of the levels studied, strong molecular enhancements in the populations were observed, the enhancements being especially large for some highlying yrast terms. It is suggested that at least two processes occur. (i) There is a general electron capture at the back of the foil. The overall capture probability is increased when molecules are accelerated. (ii) There is downstream from the foil a redistribution in level population caused by electrons following the projectiles. This redistribution is much more active when molecules are accelerated, due to the larger number of secondary electrons. The redistribution takes place during a surprisingly large time interval.

SODIUM-SODIUM CHARGE EXCHANGE PROCESSES STUDIED BY COLLINEAR LASER SPECTROSCOPY

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The charge exchange process has permitted to extend collinear spectroscopy technique, initially developed on fast ionic beams, to the case of neutral atomic beams[1,2]. Conversely, laser spectroscopy turns out to be helpful for studying charge transfer mechanism as pointed out by Anton et al[3].

Following this idea, we have studied charge exchange collisions between a fast monokinetic Na^+ beam and a Na vapour. Two processes occur concurrently :

(1) $Na^+ + Na(3s) \rightarrow Na(3s) + Na^+$ (resonant channel)

(2) $Na^+ + Na(3s) \rightarrow Na(3p) + Na^+ + \Delta E \rightarrow Na(3s) + Na^+ + \Delta E + h\nu$ (non resonant channel).

The energy defect ΔE ($\simeq 2,1$ eV) of channel (2) is taken from the kinetic energy of the fast incident ion. Each resonance line appears as a main peak with a small satellite on the low velocity side. The intensity ratio ρ of these two peaks is directly related to the ratio of the cross-sections of reactions (1) and (2).

At low vapour pressure ($p \leqslant 10^{-3}$ Torr) we have measured $\rho_{lim} = \frac{\sigma_{non\ res.}}{\sigma_{res.}} = 5.5\ 10^{-2}$. At higher pressures, multiple collision processes become important :

$$Na(3s) + Na(3s) \rightarrow Na(3p) + Na(3s) + \Delta E \rightarrow Na(3s) + Na(3s) + \Delta E + h\nu \qquad (3)$$

or

$$Na^+ + Na(3s) \rightarrow Na^+ + Na(3p) + \Delta E \rightarrow Na^+ + Na(3s) + \Delta E + h\nu \qquad (4).$$

At a pressure $p > 10^{-1}$ Torr, we have counted up to 8 equidistant peaks in the fluorescence signal, showing that some atoms experience seven successive collisions of type (3) or (4).

Other experiments with beam energies in the 1 keV - 50 keV range are planned since the non resonant channel cross-section is expected to increase rapidly with the beam energy compared to the resonant one[4,5]. Precise measurements of the vapour density and length are required too in order to extract absolute cross-section values.

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ORIENTATION OF HE I n^1D- AND n^3D- TERMS AFTER ION BEAM TILTED FOIL INTERACTION

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The circular polarization fraction S/I of the emitted light of transitions from HeI n^1D and n^3D ($3 \leq n \leq 7$) is studied after the interaction of 300keV He^+ - ions with a thin carbon foil which is tilted with respect to the beam axis. In the first part of the experiments the dependence of the polarization on the irradiation dose of the foil is investigated and it is found that reliable polarization measurements can be performed as long as the foil does not show a macroscopic destruction. Then the dependence of S/I on the current density of the incoming beam is measured and a pronounced effect is observed.

The measurement of the circular polarization S/I of transitions starting from nd-terms in the singlet and triplet system of He I shows a monotonic increase in S/I as a function of the principal quantum number n up to n = 6. Furthermore a distinct spin effect is observed in the data; i.e. the polarization in the triplet transitions is found to be larger than in the singlet transitions which contradicts the assumption of an orbital angular momentum excitation process and the coupling with isotropically distributed spins.

In addition to these experiments the He^+ - ions were scattered from a solid and highly polished Cu-surface at grazing incidence and the results are compared with the tilted foil data.

FAST BEAM EXCITATION OF THE $1s^2 2s2p3d\ ^2D$-TERM IN NEUTRAL BORON

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After the excitation of a fast boron ion-beam (18keV-120keV) by a gastarget, a solid surface at grazing incidence, or a thin carbon foil we observe a pronounced emission of light at 582nm. In the available spectroscopic data this line is not classified. By applying a charge state sensitive detection technique we find that the unknown line is emitted in the spectrum of neutral boron. In the second step of our experiments we resolve the fine-structure of this transition by observing the light emission after gas-target excitation in "end-on"-geometry.

From these results we attribute the line at 582nm to the $2s2p^2\ ^2P-2s2p3p\ ^2D$ - transition in doubly excited neutral boron. For $2s2p3p\ ^2D$ we derive term-energies $E(J=3/2) = (89705.0\pm0.6)cm^{-1}$ and $E(J=5/2) = (89708.7\pm0.6)cm^{-1}$ and a fine-structure splitting of $(3.3\pm0.2)cm^{-1}$. As a check of consistency serves the observation of two further previously not classified transitions of medium intensity. These two transitions observed at (238.86 ± 0.03)nm and (286.11 ± 0.03)nm can be derived from the term-energies of the $2s2p3d\ ^2D$-term and we compute for the $2s2p^2\ ^2D-2s2p3d\ ^2D$ - transition a wavelength of (238.87 ± 0.01)nm and for $2s^2 3d\ ^2D-2s2p3d\ ^2D$ (286.12 ± 0.01)nm.

POST COLLISION STARK-EFFECT INTERACTION AFTER ION BEAM SURFACE INTERACTION AT GRAZING INCIDENCE

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After the interaction of fast ions with a solid surface at grazing incidence a large orientation in the distribution of the orbital angular momenta along $\vec{n} \times \vec{v}$ ($\vec{n}$ = surface normal, $\vec{v}$ = ion velocity) is observed[1] which can be monitored by the circular polarization fraction S/I in the fluorescent light. A deviation from this sense of orientation was reported by Fröhling[2] and Graser and Varelas[3] for the HeII n'=3-n=4 transition and interpreted in terms of a post collision Stark-effect interaction in the electric field at the surface[2].

I, rder to investigate this process in more detail we performed ·'ter the ion-surface interaction with the help of a horizontal slit a scattering angle dependent detection of the polarization. By this method of detection we probe the effect on different trajectories, i.e. the time the ion or atom spent in the electric field at the surface which mixes opposite parity levels. The experiments show an inversion of polarization when varying the angle of exit for levels in hydrongenlike HeII, whereas for levels in HeI and HI no dependence of the polarization on the angle of exit is found.

From these results we deduce that the excitation of these terms takes place at a distance from the surface where the surface electric field is already too small to cause an appreciable Stark-mixing. The field which is responsible for the observation in hydrogenlike HeII is due to the image charge of the receding ion. This field is in comparison to the surface electric field long ranging and leads to a modification of the anisotropy of the initial excitation process.

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SUBSHELL-SELECTIVE ELECTRON CAPTURE BY SLOW MULTIPLY CHARGED IONS FROM Li ATOMS

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Electron capture by slow ($v < 1$ a.u.) multiply charged ions (MCI) from Li(2s) can be described within quasi-one electron collision systems. For primary ion charge states $q \geqslant 2$ the capture dominantly populates highly excited final states which are nearly degenerate in binding energy. Thus the primary ion species is less significant for the capture processes than the ion charge state q, and different electronic configurations of the MCI will remain almost completely conserved[1] during the capture processes.

In our experiments MCI beams have been produced by an ECR ion source[2] and crossed with a Li atom beam. Excited final states have been observed by means of intensity-calibrated grating spectrometers in both the vuv and the visible spectral regions.

Results of a detailed study on (n,ℓ)-subshell capture will be presented for C^{4+}-Li(2s) collisions at impact energies from 10 to 80 keV[3]. Furthermore, it will be shown how primary MCI core conservation for capture from Li(2s) could be demonstrated and was utilized for determination of metastable ion beam fractions with Be-like and B-like MCI[1]. These fractions were found to be completely independent on the ECR source operating parameters and agreed fairly well with calculations, assuming stepwise electron impact ionisation and ion loss due to limited confinement in the source plasma as the dominant processes for the ECR source plasma ionisation balance[1]. Finally, it will be discussed in which way photon emission from MCI excited via electron capture from Li can be utilized to detect low-Z impurity ions in the boundary region of hot magnetically confined plasmas[4]. We present absolute emission cross sections[5] for electron capture-induced line radiation for $C^{q+}(3 \leqslant q \leqslant 6)$ and $O^{q+}(4 \leqslant q \leqslant 7)$, which show that the proposed new diagnostic technique might indeed be feasible.

Acknowledgments

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POSTER SESSION B

ABSTRACTS 72 - 104

LASER-PLASMA SPECTRUM OF HIGHLY-IONIZED GOLD (4.4 - 6.2 Å)

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The spectrum of gold (Z = 79) which we have studied between 4.4 and 6.2 Å has been emitted by a laser-produced plasma.

For analysing it, we have used the method of the Relativistic Parametric Potential[1], which yields accurate results in highly-ionized atoms. In this method, an analytical central potential is first optimized, through the minimization of the total energy of a few low relativistic configurations of the ion. Then the eigen-states are deduced, through the diagonalisation of the Hamiltonian in a jj-coupled basis[2].

The studied spectrum exhibits strong lines due to the transitions $3d^{10}-3d^9 4f$, $3p^6 3d^{10}-3p^5 3d^{10} 4s$ and $3d^{10}-3d^9 4p$ in the Ni I-like Au^{+51} ion, and the following " satellite " features:

(i) at longer wavelengths, the lines of the ions Au^{+50}, Au^{+49} and Au^{+48}, belonging respectively to the isoelectronic series of Cu I, Zn I and Ga I, and deriving from the Ni I-like transitions through the addition of one or several 4s and/or 4p electrons;

(ii) at shorter wavelengths, the Au^{+52} lines, in the isoelectronic series of Co I, due to the transitions $3d^9-3d^8 4f$, $3p^5 3d^{10}-3p^5 3d^9 4f$, $3p^6 3d^9-3p^5 3d^9 4s$, $3d^9-3d^8 4p$, $3p^5 3d^{10}-3p^5 3d^9 4p$.

Each satellite feature appears in the spectrum as a transition " sub-array ", in which the individual lines are unresolved.

We give predicted wavelengths for the intra- and interconfigurational transitions in and between the low configurations $3p^6 3d^9$ and $3p^5 3d^{10}$, and for the lines emitted from the higher-excited 4d, 5p and 5f orbitals.

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ASYMMETRY OF TRANSITION-ARRAY PATTERNS

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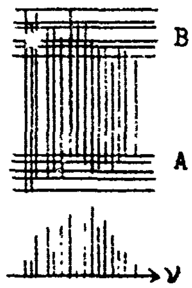
A method has been developed recently[1] for evaluating directly the wavenumber average and r.m.s. deviation of the lines of a transition array, i.e., all the transitions between two electronic configurations A, B. For such an evaluation, only the values of the radial Slater and spin-orbit integrals, and of the configuration average wavenumbers, are needed, but not the individual lines, which may be very numerous and/or unresolved.



In the present work, we have improved this crude description through the direct evaluation of the third-order moment of the array, μ_3^c, and of the asymmetry coefficient $\alpha_3 = \mu_3^c/\sigma^3$ (σ being the r.m.s. deviation of the array), in the case of $l^{N+1}-l^N l'$.

For achieving this huge task in an economical way, we have assumed that all the relevant orbitals are hydrogenic for the same value of the effective nuclear charge Z , so that the ratios between the Slater integrals are independant of N and Z . After α_3 has been determined, it is possible to represent the array through a " skewed Gaussian " function of the wavenumber, as defined by Croxton[2]. This new description brings in two changes:

(i) the maximum of the skewed Gaussian is shifted with respect to the average wavenumber;

(ii) its full width at half maximum is smaller than that of the simple Gaussian proposed previously[1].

The asymmetry appears to be maximum in the $d^{N+1}-d^N f$ series, when N is large. We have found experimental confirmations in a Xenon spectrum of a Tokamak.

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ARGON INJECTION IN FT TOKAMAK PLASMA

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H-like Argon line spectra have been recorded by means of a high-resolution crystal spectrometer, following puff injection during a tokamak discharge, in a small range of temperature and density plasma conditions ($T_e \simeq 1.2$ keV, $n_e \simeq 10^{14}$ cm^{-3}).

Accurate wavelengths determination shows good agreement with theoretical predictions. Second order diffraction of He-like Iron, occurring at the same Bragg angle, permits an interesting wavelength comparison.

Argon line intensities have been computed, in order to determine both the $L\alpha_2/L\alpha_1$ and the dielectronic satellite to resonance line ratios, the former showing a small increase over the usual 0.5 value towards the end of the discharge due to recombination effects, and the latter allowing the calculation of a plasma electron temperature in fairly good agreement with Thomson scattering measurements. Finally, plasma ion temperature is deduced by Doppler broadening of the resonance lines.

STUDIES OF 1s2s ^3S - 1s2p ^3P TRANSITIONS IN HELIUM-LIKE Ne^{8+} RECOIL IONS USING PHOTOGRAPHIC SPECTROSCOPY

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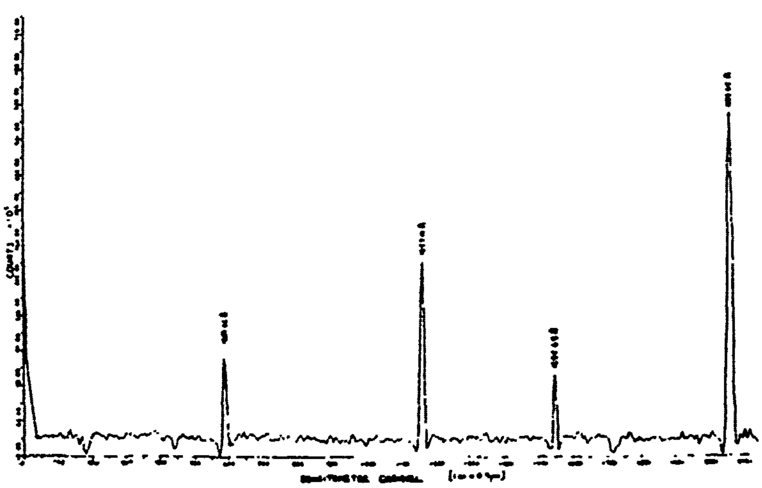
This work is a continuation of a programme of spectroscopy of helium-like ions started in Oxford several years ago. The aim is to make accurate measurements of the wavelengths of the 1s2s ^3S - 1s2p ^3P transitions, which may then be used for a stringent test of relativistic and quantum-electrodynamic effects for the electrons bound in the helium-like ion under study.

The potential of the recoil ion technique for these measurements was first investigated by Klein et al[1,2] and Gould[3], whilst the most precise measurements of these intervals to date, for ions with $Z>3$, appear to come from photographic spectroscopy of tokamak plasmas containing helium-like ions of impurity elements (Stamp[4]). It seemed natural to combine these two approaches in an attempt to obtain increased precision of wavelength measurements in recoil-ion sources and work started on a photographic study of VUV spectra in recoil-ions of Neon last year, using projectile beams of Bromine from the University of Oxford EN tandem accelerator to produce the required highly stripped recoils in Neon gas targets.

Initial results have been encouraging, with spectral resolutions of $\sim$ 0.03A at 1250A, and we envisage eventual wavelength accuracies of a few p.p.m. Some of our spectra have been digitised using the University of Cambridge APM device, and Fig. 1 shows a portion of a typical spectrum of a Neon target processed in this way:



Work is also progressing on the construction of our own micro-computer controlled digital microdensitometer, which will have a positional accuracy of about 1μm.

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PRECISION X-RAY SPECTROSCOPY ON 8.5 MeV/amu HEAVY IONS

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A new experimental capability has been developed at the Lawrence Berkeley Laboratory Super-Hilac to investigate several questions relating to atomic spectroscopy.

A key element to the success of these measurements is a novel dual arm Johann spectrometer specifically designed for these experiments. The ion beam passes inside the Rowland circle of two curved crystals which are mounted coplanarly such that diffracted x-rays have equal and opposite linear Doppler shifts. The x-ray lines are detected with high speed x-ray film mounted on the Rowland circle. The beam-crystal geometry is arranged so a large spectral range is detected ($\theta_B \approx 30°$ to $70°$). The spectrometer efficiency is extremely high with useful exposures obtained with only 1 millicoulomb of beam. A calibration is obtained by simultaneously exposing the film with diffracted K and L x-rays from an x-ray tube. X-rays from the beam are slanted with respect to the calibration lines due to Doppler shifts arising from x-rays incident on the crystal at angles other than perpendicular to the diffraction plane. The slope of this line can measured and it provides an independent determination of the beam velocity, which is used to correct for the transverse Doppler shift. Typical results are illustrated in Table 1 and Fig. 1.

Table 1

Ly-α Fine Structure Intervals

Element	Current Results	Theory
Fe	21.5 ± .5	21.2 eV
Zn	38.6 ± 1.4	37.9 eV

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

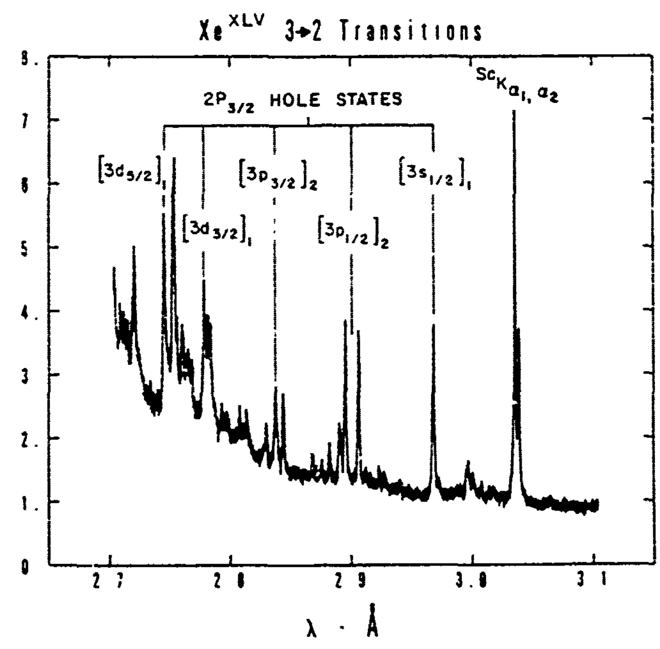

Fig. 1

CHARGE EXCHANGE OBSERVATIONS AND ANALYSES IN THE DITE TOKAMAK

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Measurements of line intensity enhancement from C and O ions during beam injection of neutral hydrogen into the DITE tokamak has been measured for a neutral beam energy of 25 keV and for beam powers of up to 2MW. Observations of the spectrum from O^{7+} encompass the Lyman series in the XUV region (1s-np, $p \lesssim 8$) and $\Delta n=1$ transitions in the VUV and visible spectral regions. The different selection rules for these transitions allow the measurement of the effective cross section for charge exchange as a function of the optical electron angular momentum. The interpretation takes into account radiative cascade and ℓ-state mixing for the plasma conditions during observation.

L^2 REPRESENTATION OF THE CONTINUUM IN COLLISIONS BETWEEN ALPHA-PARTICLES AND LITHIUM ATOMS.

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We report close-coupling two-centred atomic orbital calculations of single-electron charge exchange, excitation and ionisation in collisions between He^{2+} and Li in the intermediate energy range, using a square integrable (L^2) representation of the continuum. In the usual impact parameter formalism for heavy particle collisions we initially choose a L^2 finite basis and variationally optimize the time dependent amplitudes to produce the physical cross sections. We estimate the ionisation contribution by considering the projection of the complete basis onto the numerical positive energy solutions of the corresponding Schrodinger equation. For the reactions in question, it is well known that the calculated cross sections may differ significantly from experiment, over a certain range of energies, when pseudo-continuum states are omitted from the basis. We investigate the problem of preselecting the discrete basis set so that only a minimal number of states are required to produce adequate results, in terms of convergence. We examine the simplest method of choosing the basis by demanding a good representation of certain oscillator sums over the positive energy interval and optimizing the overlap with the continuum. We discuss the relation between this method and a more general method of Langhoff et al (1974) which produces so-called principal pseudo-states whose eigenvalues and oscillator strengths define a Gaussian type quadrature scheme over the spectral sums. We consider also the quality of the bases used, in the light of the energy width criteria suggested by Reading et al (1979).

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HIGH PRECISION WAVELENGTH DETERMINATIONS
IN SPECTRA EMITTED BY THE He-LIKE and H-LIKE IONS
DURING SOLAR FLARES

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The Naval Research Laboratory (NRL) obtained many high resolution X-ray flare spectra from a number of Bragg Crystal Spectrometers flown on an orbiting spacecraft (P78-1) launched by the U.S. Air Force on 24 February 1979. Two of the Bragg spectrometers recorded spectra in the 2.96 - 3.10 Å and 3.12 - 3.25 Å wavelength ranges. Analysis of these spectra revealed the presence of weak lines of Ar XVII, Ar XVIII, K XVIII and Fe XXV near the strong $1s^2$ - 1s2p and 1s - 2p lines of Ca XIX and Ca XX. Using theoretical wavelength calculations of one of the H-like lines, we were able to determine the wavelengths of the rest of the lines and thus compare the measured results with recent calculations of H- and He-like spectra. A detailed discussion of the above mentioned spectra will be given.

VARIATIONAL REPRESENTATION OF THE DIRAC SPECTRUM

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A new variational representation of the Dirac equation is presented. The basis set is required to satisfy some general energy-independent conditions at the origin. The method is applied to the case of a Coulomb potential. The resulting variational solutions form a discrete representation of the complete Dirac spectrum including both positive and negative energy states *without spurious roots*. The variational eigenvalues satisfy a generalized Hilleraas-Undheim theorem.

MOLECULAR THEORY OF ATOMIC COLLISIONS:

A GENERALIZED PERTURBED STATIONARY STATES APPROACH

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The perturbed stationary states equations, which describe low velocity atomic/ionic collisions using continuum states of the aggregate molecule[1] have been generalized to include the effects of electron translation.[2] The generalized nuclear scattering equations reduce to those of the perturbed stationary states method as the electron mass tends to zero. As either nuclear charge tends to zero, the solutions describe the translation of a free atom.

The extraction of the proper T-matrices from the nuclear scattering solutions is a major difficulty in the molecular description of atomic collisions since molecular coordinates are not asymptotically appropriate. To this end we have examined asymptotic limits of the Fadeev equations[3], written in terms of potentials rather than the usual transition operators, to obtain the proper scattering boundary conditions and expressions for the inelastic, rearrangement and ionization T-matrices.

The theory is applied to charge transfer reactions involving low velocity collisions of hydrogen atoms with bare nuclei.

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ENERGY-LEVEL SCHEME AND TRANSITION PROBABILITYES OF Al-, Si-, AND P-LIKE IONS*

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Theoretical energy levels and transition probabilities are presented for low-lying levels of aluminum-, silicon-, and phosphorus-like ions. The multiconfiguration Dirac-Fock technique[1] is used to calculate energy levels and wave functions. A Dirac-Fock wave function consists of Slater determinants of relativistic one-electron orbitals, which are obtained from the usual self-consistent-field procedure with the Dirac hamiltonian. Electron correlation effects are accounted for by including many electronic configurations in the self-consistent-field procedure. Contributions from the Breit interaction and the Lamb shift, which includes self energy[2] and vacuum polarization,[3] are treated as a first-order perturbation. The electric-dipole, electric quadrupole, and magnetic-dipole transitions between levels are also calculated.

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MULTICONFIGURATION RELATIVISTIC RANDOM-PHASE APPROXIMATION AND ITS APPLICATION*

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Multiconfiguration relativistic random-phase approximation[1,2] is developed to describe excitations of an atomic system having a multiconfiguration ground state. The response of such an atom to an imposed harmonic perturbation is determined by applying the time-dependent variational principle to a multiconfiguration wave function constructed from Dirac orbitals. Terms in the wave function independent of the external field lead to the multiconfiguration Dirac-Fock description of the ground state. Terms proportional to the external field lead to a multiconfiguration generalization of the relativistic random-phase approximation. Application of the multiconfiguration relativistic random-phase approximation theory to resonance transitions in Be-, Mg-, and Zn-like ions are presented. Treatment of parity-nonconserved interactions with this new theory is also discussed.[3]

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Identification of Fe XVIII in solar flares based on isoelectronic extrapolations

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Around twentyfive lines in solar flare spectra in the region 200 - 500 Å have been identified as transitions between the $2s^2 2p^4$ 3s, 3p and 3d configurations in Fe XVIII. The isoelectronic study is based on newly made analyses of S VIII, Cl IX and published results of highly ionized Ti by Bashkin et al. [1]. The identifications are based on isoelectronic extrapolations of differences between experimental and theoretical wavenumbers along the fluorine-like sequence.

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PLASMA-ATOMIC X-RAY SPECTROSCOPY AT TOKAMAKS

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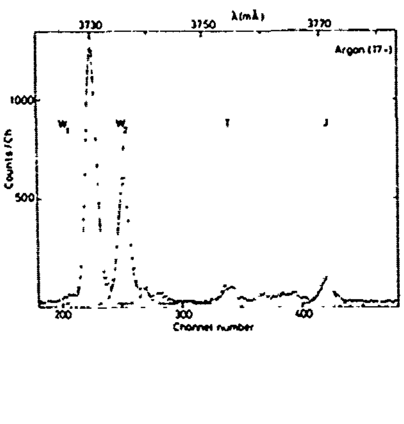
High resolution ($\Delta\lambda/\lambda$ < 1/2000) x-ray spectroscopy is commonly used to measure the line emission from impurities in high temperature (T_e>0.5 keV) plasmas of both man-made and astrophysical origin. The study of H- and He-like spectra of elements up to Fe has been popular since the measured line widths (Doppler broadening) and line intensities present means to diagnose the plasma conditions under which the excited states of the x-ray transitions were formed. The principal parameters of laboratory plasmas are usually known through independent diagnostic measurements so that plasma-atomic x-ray spectroscopy at tokamaks can be used to study atomic processes under partially known and controllable conditions.

During the last few years we have done extensive measurements of the H- and He-like spectra of S, Cl and Ar at the Alcator C tokamak at MIT. In these studies we have used spectrometers of the von Hamos geometry and a matching multiwire proportional counter of novel type was developed for the x-ray detection. The detector has a spatial resolution of Δx<150 µm at count rates of >0.2 MHz over a single line and up to 1 MHz over the full detector length of 35 mm; work is in progress to increase the rate capability and to extend the detector length to 110 mm. The design goal for this spectrometer is a bandwidth of $\delta\lambda/\lambda$ = 10% (to measure H- and He-like spectra, simultaneously), which is selectable over a spectral range of λ= 1.5 to 5 Å (in order to study ions of Z between 16 and 28), and a count rate capability in excess of 1 MHz; i.e. a broad band, large dynamic range, high-resolution instrument for time resolved spectroscopy of transient phenomena at the 1 ms level.

In this contribution we shall present the new spectrometer system and the envisaged capabilities will be demonstrated with recent results obtained with a prototype instrument. These results include the first radial scan measurement of the H- and He-like emission for Ar, i.e., over the range of R=0 to 13 cm for a plasma radius of 16.5 cm and the temperature range T_e = 1.4 to 0.3 keV; an example of an H-like spectrum at R=0 is shown below. We identify three plasma regions dominated in turn by x-ray emission due to (1) excitation through electron impact and dielectronic recombination, (2) radiative recombination and (3) charge transfer recombination $D + Ar^{17+} \rightarrow D^+ + Ar^{16+}$; the sensitivity of the latter process is $N_0/N_e \cong 10^{-5}$ for n=2 to n=1 transitions and can be increased by studying $\Delta n \cong 10$ transitions instead of Δn=1. Results on transient phenomena will be presented from the rise and decay phases of the plasma discharge as well as during pellet fuelling injections. As for earlier studies, we compare the data on line intensity ratios with detailed atomic rate calculations for given plasma conditions. However, in the present time resolved data for single discharges we detect non-equilibrium effects in the recombination and ionisation phases of the plasma as well as ion-transport effects in peripheral plasma regions. With these results we demonstrate that high-resolution time-resolved spectroscopy contains a wealth of information on the atomic rates involved in the x-ray transitions observed and that this information could be extracted with the help of comprehensive theoretical analysis including the entire H- and He-like spectra, first separately and eventually the two together when such data become available.



INTENSITIES IN COMPLEX SPECTRA OF HIGHLY IONIZED ATOMS

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We describe a package of programs for the implementation of the collisional-radiative model to complex configurations. The number of levels taken into account may be several hundreds. The heart of the package is a very efficient program for excitation cross sections in the Distorted Wave framework, using the Relativistic Parametric Potential wavefunctions. The basic jj coupling scheme actually simplifies the computations, enabling a useful factorization into radial and angular parts. Intermediate coupling and configuration interactions are accounted for. We computed ratios of intensities of $3d^9$-$3d^8 4s$ (E2) to $3d^9$-$3d^8 4p$ (E1) transitions as functions of n_e and T_e in Xe XXVIII and other Co-like spectra. The atomic model involves all the levels of configurations $(3p^6)$-$3d^9$,-$3d^8 4s$, -$3d^8 4p$,-$3d^8 4d$,-$3d^8 4f$, and $(3p^5)$-$3d^{10}$, $3d^9 4p$. (275 levels) and all the transitions between them. Results compare very well with experimental spectra from TFR.

NEW RESULTS OF THE UNRESOLVED TRANSITION ARRAYS METHOD

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The formulas for mean wavelengths and widths of Unresolved transition arrays (UTA) (1,2), have been extended to include spectator electrons and jj transitions. These were used to interpret several sorts of satellite spectra, e.g. $3d^{10}n\ell^{q}$ -$3d^{9}4fn\ell^{q}$ transitions in atoms Tm thru W from laser produced plasmas, and $3d^{m}4s$-$3d^{m-1}$ 4p4s in Mo and Pd spectra. The Unresolved Character of the UTA will be discussed thanks to an evaluation of the number of lines in the array. This will be applied to 4d-4f transitions in Ionized Rare Earths.

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MICROPINCH AS A SPECTRAL SOURCE OF HIGHLY IONIZED ATOMS

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The phenomena of the so called "plasma points" in plasma column of discharge with axial symmetry was treated in /1/ as a result of contraction of a Z pinch due to outflow of plasma and radiative energy loss. A semiempirical formula for line-radiative losses taking into account density effects and simple opacity approximation was constructed. "Equilibrium" parameters of micropinch (MP) can be derived from the balance between energy losses and heating of plasma. It was assumed also that the Bennet's "quasiequilibrium" between plasma pressure and magnetic field is valid. Time history of the neck was calculated on the basis of "simple model" of plasma outflow /2 /.

Approximate but useful Z_n- and I- (current,Ma)-scaled formulas expressing some of the results are obtained: 1. Dimension of MP essentially depends on elements contained in the plasma: $a \approx 500\ I^{0.833}/Z^2 T_e$ (Z_n- the nuclear charge, T_e-the electron temperature-ev). For the stage of evolution when K-ions (H-,He-like) exist - $a_k \approx 200\ I^{0.833}/\ Z^4$ cm. 2. Electron density of MP plasma increases with Z_n: $n_e \simeq 2 \cdot 10^{15}\ I^{0.33} Z^4 T_e$ cm^{-3} and for "K -stage" $n_{ek} \simeq 5 \cdot 10^{15} I^{0.33} Z^6$ cm^{-3}. 3. For a given current I "K-stage" can be achieved only for elements with $Z_n \leqslant (60...70)\ I^{0.33}$. 4. The time of MP evolution beginning from the moment when $T=Z^2$ $\tau \simeq 3 \cdot 10^{-3}\ I^{0.833}/\ Z^5$. $\frac{d(n_e\tau)}{dT} \simeq (3...10)\ 10^{13}\ I^{1.166}\ Z^2/\ T_e^{1.5}$.

The values of MP plasma parameters derived from the above formulas are in a good agreement with experimental ones for moderate currents (0.2...0.3MA) and $Z_n \leqslant 40$. So we hope that our calculations will be useful for estimating the capability of MP plasma as a source of highly ionized atom spectra.

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TRANSITION RATES FROM DYNAMICALLY OPTIMIZED WAVE FUNCTIONS: POSITRON EMISSION BY HEAVY ION IMPACT

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We have investigated electron excitation during heavy ion collisions. The idea is to parametrize and optimize the electron's wave function according to the various multipole excitation modes. By this method one obtains the time-dependent optimum path of the electron in phase space.[1]

The corresponding approximate solution of the time-dependent Dirac equation is easy to compute. The solution is, however, a mean field approximation because intrinsic generator coordinates are used. From this mean field transition amplitudes T_{if} can be extracted[2]. In addition to the usual overlap of initial and final state wave functions after the collision one needs an integral term that takes care of the error $|\varepsilon\rangle = \left(H - i\hbar\frac{\partial}{\partial t}\right)|\chi_i\rangle$ during the collision:

$$T_{if} = \langle \chi_f | \chi_i \rangle \Big|_{t\to\infty} + \frac{1}{i\hbar}\int_{-\infty}^{\infty} \langle \chi_f | H - i\hbar\frac{\partial}{\partial t} | \chi_i \rangle \, dt \, . \qquad (1)$$

The second term has turned out to be most important, and it is possible to calculate the positron emission rates for heavy ion collisions to the correct order of magnitude. (cf Fig. 1)

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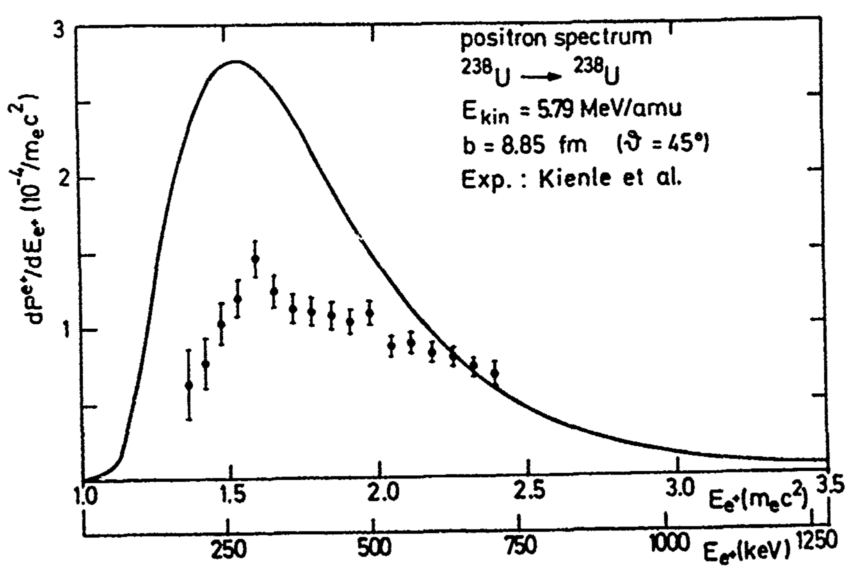

Fig. 1: Positron production during an U → U collision. The experimental data are from Ref. 3.

POSITRON SPECTROSCOPY IN ELASTIC AND DISSIPATIVE HEAVY ION COLLISIONS+

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In very heavy ion encounters the electrons experience for a short time the united charge of the two nuclei building a quasi atom[1]. During the collision the Coulomb potential changes rapidly and induces the emission of electrons from all levels - including the Dirac sea. As the spectral distributions of the emitted e^- and e^+ reflect the Fourier frequencies of the time evolution of the collision process, they are sensitive to perturbations of the Coulomb trajectories due to nuclear contact in close collisions[2].

Our experimental program is devoted to the study of time-delay effects in such dissipative reactions. In recent experiments performed with the new TORI Spectrometer[3] at the GSI we measured positrons, δ-electrons and gamma rays after elastic and dissipative U + U reactions at beam energies from 5.9 up to 10.0 MeV/u. As an example, Fig.1 shows atomic positron spectra for the U + U collision system at 8.4 MeV/u, measured in coincidence to elastic scattering and to sequential fission events indicating dissipative reactions. The spectra are corrected for the efficiency of the detector and positrons originating from pair conversion of nuclear transitions are substracted. In contrast to the upper spectrum the high energetic decline in the lower one is steeper than expected under the asumptions of pure Rutherford trajectories. This results from phase-shift effects between ingoing and outgoing positron production amplitudes, caused by a contact time which varies between T = 0 (grazing collisions) and $T = 1.5 \cdot 10^{-21}$s (central collisions) according to a quantitative analysis[4].

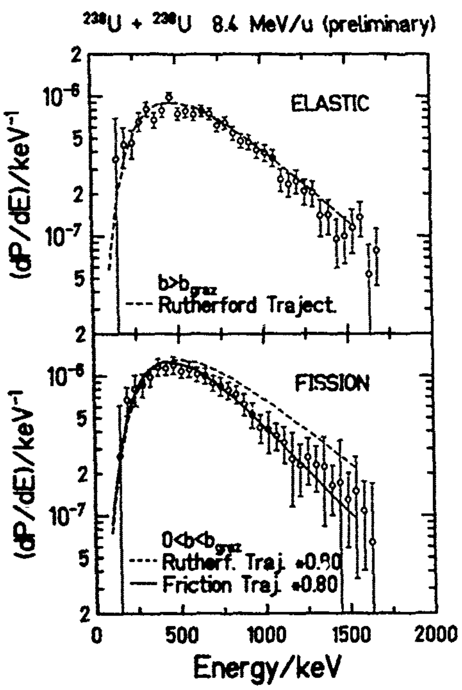

Fig.1: Positron spectra from U + U collisions at 8.4 MeV/u in coincidence to elastic and quasielastic scattering and to fission reactions.

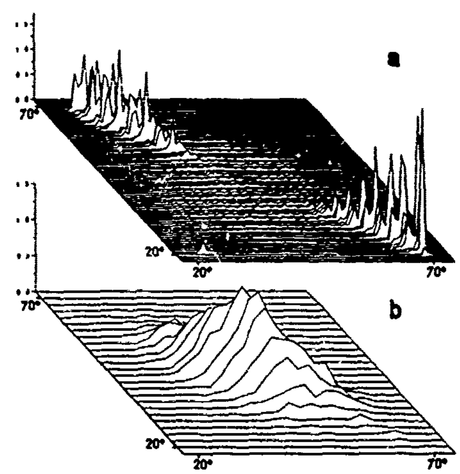

Fig.2: U + U 8.4 MeV/u:
a) Kinematical coincidences between the emitted fragments exhibiting the two classes: elastic scattering and deep-inelastic collisions observed by the broad $(\vartheta_1,\vartheta_2)$-correlation of the fission products.
b) Subclass of 4-body events shown as a function of mean angles between pairs of fission fragments.

Elastically scattered heavy ions are separated from fission fragments by their kinematic $(\vartheta_1,\vartheta_2)$-correlation. This is demonstrated in Fig.2a, showing a 2-dimensional plot of the polar angles of the reaction products for the U + U reaction at 8.4 MeV/u.

Oscillatory modulations in the δ-electron and positron spectra are predicted for narrow time-delay distributions[5]. In a first experiment concerning this question subgroups in impact parameter or Q-value could be selected by dividing the fission reactions into 3- and 4-body events. Fig.2b shows the subclass of identified 4-body events for the reaction U + U at 8.4 MeV/u, plotted versus the averaged measured scattering angles of two fission fragments.

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+) Supported by BMFT

CALCULATIONS ON QUARTET LEVELS OF 3-ELECTRON IONS

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Core-excited quartet levels of 3-electron ions are a subject of continuing experimental and theoretical interest. The quartet spectra of Li I and Be II have been very thoroughly investigated and are well understood. The quartet spectrum of B III has received some attention experimentally[1] but only a relatively small number of assignments have been made and lifetime measurements have not yet been performed. Some of these assignments are certainly incorrect and further experimental work, utilising a beam-foil source, is currently being undertaken[2] to help elucidate the B III quartet term diagram.

Theoretical calculations will continue to play an important rôle in the identification of observed beam-foil spectra. We are using a model-potential method to predict wavelengths and transition probabilities for lines in the quartet spectra of 3-electron ions. We also calculate radiative decay lifetimes for the levels, quantities which can be a valuable aid in the assignment of observed lines. Table 1 presents a sample of our results for B III and our calculated transition wavelengths are compared with experimental values. The majority of previous assignments are not correct.

Details of our procedures, including convergence studies of our wavefunction expansions, alternative assignments for observed lines and photoionisation cross sections for metastable $1s2s2p\ ^4P^0$ levels will be presented at the meeting.

Table 1. Experimental and theoretical data for B III quartet lines.
* denotes an incorrect assignment.

Transition		Wavelength (Å)		Transition probability ($10^8\ s^{-1}$)	Lifetime of upper level (ns)
		Experimental[1]	Calculated		
$2s2p\ ^4P^0$	$-2s3d\ ^4D$	457.7	457.1	119.1	0.084
	$-2s4d\ ^4D$	367.8	367.5	38.4	0.23
	$-2s5d\ ^4D$	338.4	338.1	20.0	0.41
$2p^2\ ^4P$	$-2p3s\ ^4P^0$	567.2	566.8	23.5	0.41
	$-2p3d\ ^4P^0$	493.1	492.3	52.4	0.18
	$-2p3d\ ^4D^0$	499.4	499.1	116.7	0.085
$2s2p\ ^4P^0$	$-2s3s\ ^4S$	524.4*	518.7	34.0	0.29
	$-2p3p\ ^4S$	408.6*	402.2	25.8	0.36
$2p^2\ ^4P$	$-2p4s\ ^4P^0$	423.7*	414.7	6.5	0.88
	$-2p4d\ ^4D^0$	402.7*	399.5	45.5	0.20

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LAMB SHIFT MEASUREMENTS IN HIGH Z HYDROGENIC IONS

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The $1s^2S_{1/2}$-$2p^2P_{1/2,3/2}$ transition energies in hydrogen and hydrogenic ions may be calculated analytically using the Dirac equation, with small corrections for finite nuclear mass and size, and for hyperfine structure if the ion has nuclear spin. Further corrections are predicted by quantum electrodynamics (qed) including the electron anomalous magnetic moment and radiative level shifts. Ground state Lamb Shift measurements in high Z hydrogenic ions can then be made by accurately determining the $1s^2S_{1/2}$-$2p^2P_{1/2,3/2}$ transition energies and subtracting a calculated non-radiative value for these intervals. This is not a new idea; it is embodied in the Doctoral work of B. Edlen[1)] who noticed a discrepancy between his measured value for the $1s^2S_{1/2}$-$2p^2P_{1/2,3/2}$ transitions in Li^{++} and calculated (non-qed!) values, and the same principle has been used by G. Herzberg[2)] for a measurement in He^+.

The use of this technique was proposed in connection with fast beam sources of high Z hydrogenic ions some six years ago. More recently another possible technique was proposed: intercomparison of Lyα and Balmer β transitions in the hydrogenic ion under study. This latter proposal has similarities with the experiments of Hansch et al in neutral hydrogen,[3)] and takes advantage of the fact that, in the absence of relativistic effects, the energies of the n=1-2 Ly α and the n=2-4 Balmer β transitions are in the ratio 4:1. Since the Ly α and Balmer β transitions in the ions we wish to study are in the X-ray region, we may make a "differential" measurement of the $1s^2S_{1/2}$ ground state Lamb shift, via simultaneous observation of the Ly α and Balmer β decays in fourth and first orders of diffraction respectively, using a crystal spectrometer.

The feasibility of these difficult experiments depends crucially on the yield of X-rays which can be obtained from the source of hydrogenic ions studied. Indications from work carried out in Oxford[4)] are that the beam foil source should be of sufficient strength to justify an initial investigation of the feasibility of experiments to measure Lamb shifts in hydrogenic ions such as Kr^{35+}.

In November 1983 a Si(Li) detector was used at GSI to observe X-rays from a 19.3 MeV/A Kr^{34++} beam incident on a carbon foil. The figure shows a typical spectrum with tentative identifications of the major peaks. The data obtained give us a quantitative measure of the X-ray yield from transitions in Kr^{34+} and Kr^{35+}, and enable us to predict with some accuracy the signal strength to be expected in the next stage of the experiment. This will involve observing spectra in the same wavelength region using a curved crystal spectrometer to obtain higher spectral resolution.

This work is expected to continue at GSI and at GANIL in France.

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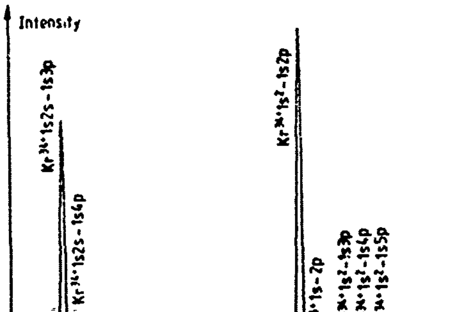

Fig. 1 Si(Li) spectrum of 19.3 MeV/A Kr^{34+} beam on 200μg/cm^2 carbon foil.

U.V. SPECTROSCOPY OF NEON RECOIL IONS

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High resolution spectra of Neon recoil ions produced by impact of Kr 20^+ projectiles at 1.15 Mev/A were recently recorded with a grazing incidence Mc Pherson 247 from 60 to 600 Å. A sample of spectra in the lower wavelength range (60-160 Å) is shown on the figure. In general, the spectra are dominated by lines from the low charge ions (Ne^{q+} $1 < q < 5$) but exhibits also lines from Ne^{6+} and Ne^{7+} Most of the lines are identified from KELLY and PALUMBO tables [1] and compared to beam-foil Spectra [2] [3] or Theta-pinch emission[4]. A number of lines are not yet determined. Calculations are on progress and the last results will be discussed at the Conference.

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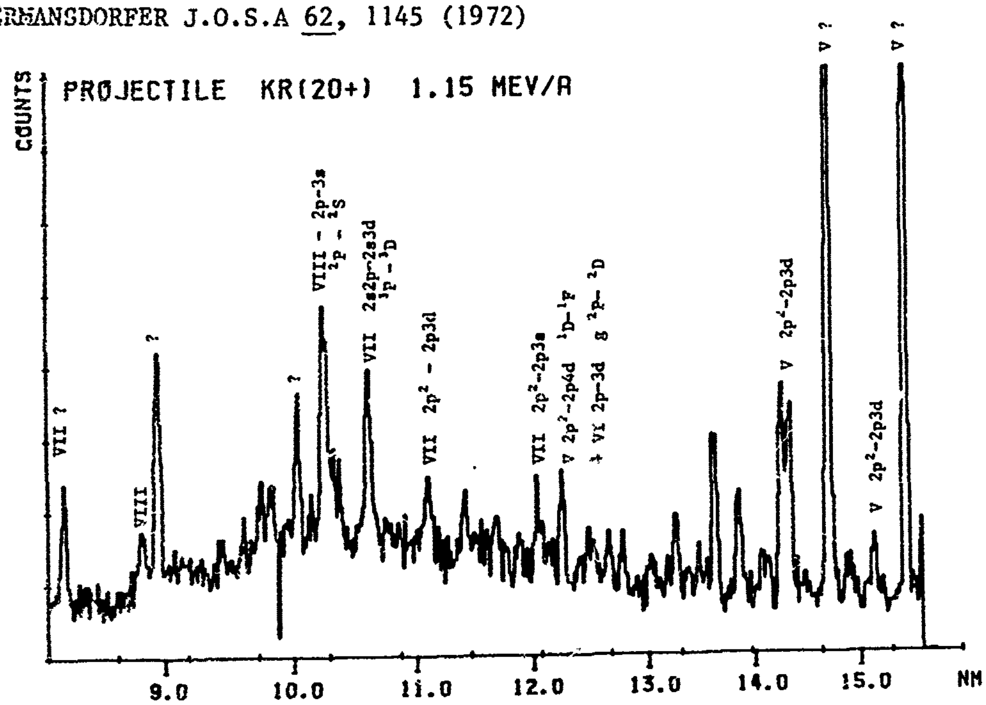

THE TFR-600 PLASMA SPECTRUM OF XENON

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The spectrum of the multicharged xenon injected in the plasma of the TFR-600 tokamak ($n_e \sim 2\text{-}8\ 10^{13}\ cm^{-3}$, $T_e \sim 1500$ eV) has been observed by means of a grazing incidence spectrograph in the range 10 -90 Å. Lines of H- and He-like carbon, nitrogen and oxygen, and of metals Ni, Fe, Cr were used as internal standards to derive the wavelengths of several dozens of xenon lines with an estimated accuracy of 0.015 Å.

The interpretation of the lines (allowed E1 and "forbidden" E2 transitions) and of the unresolved transition arrays (UTA) emitted by xenon is based on the following methods:

A- Energy level calculations by means of the relativistic parametric potential method (RELAC code [1]).

B- Comparison of the observed wavelengths with the E1 transitions of the copper-like sequence calculated by the Dirac-Fock method[2].

C- Extrapolations or interpolations of wavenumbers in well-known isoelectronic sequences (copper-like and nickel-like).

D- Parametric study of an electronic configuration by means of the Slater-Condon method and generalized least-squares fitting of the parameters on the energy levels of lighter elements of the same isoelectronic sequence[3-5].

E- Calculation of the average wavenumbers, spectral widths and asymmetries for UTA's.

The lines and UTA's interpreted so far belong to ions ranging from Xe^{25+} (copper-like xenon) to Xe^{30+} (chromium-like xenon). From the classified lines of Xe^{28+}, the energy interval $^3F_4$ - $^3F_3$ could be derived in the ground configuration $3d^8$. The corresponding magnetic M1 forbidden transition is expected at 979±10 Å.

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LASER RESONANCE STUDIES IN HIGHLY IONISED RECOIL IONS

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It was pointed our several years ago[1]) that recoil ions produced by the impact of highly charged heavy ions on target gas atoms should provide an interesting source for precise spectroscopy on account of the relatively low recoil velocities, and very recently recoil sources of helium-like neon ions have been used by the Oxford group in collaboration with GSI for precision emission spectroscopy in the VUV region of the spectrum.[2])

An interesting further development in this area will be to apply the techniques of laser resonance spectroscopy to make precise measurements of theoretically interesting atomic energy level separations in highly charged recoil ions. This work discusses the possibility of such an experiment.

Our proposal is to make an accurate measurement of the 2s $^2S_{1/2}$-$2p^2P_{3/2}$ interval in the hydrogenic Ne^{9+} ion, using an F Centre laser. Accurate measurements of energy level separations in one- and two-electron ions are of interest in that these are the simplest atomic bound systems. They are thus amenable to accurate calculations, and a comparison between theory and experiment offers a means of critically testing the theory. Of those effects which may be studied, the Lamb shift in one electron ions is of particular interest, since its origin is purely quantumelectrodynamic.

In the experiment under consideration, neon ions would be produced in a neon gas target by bombardment with highly charged heavy ions from an accelerator. The Ne^{9+} ions would then be extracted from the gas target and transported to the laser-ion interaction region, thereby selecting only the metastable states (including the $2s^2S_{1/2}$ state of interest) of the ion. The $2s^2S_{1/2}$-$2p^2P_{3/2}$ transition is calculated[3]) to lie at about 2.8μm, which is within the tuning range of an F Centre laser using colour centres in KCl or RbCl, pumped by a Kr ion laser. The resonance would be detected by tuning the laser and monitoring fluorescence on the $1s^2S_{1/2}$-$2p^2P_{3/2}$ decay in Ne^{9+}. Since the wavelength of the laser radiation is accurately known, and the expected Ne^{9+} recoil velocities are low, we may expect that an accurate value for the $2s^2S_{1/2}$-$2p^2P_{3/2}$ interval will be obtained from the measurement. Assuming that the $2p^2P_{1/2}$-$2p^2P_{3/2}$ Dirac fine structure may be accurately calculated, we can then extract a value for the Ne^{9+} $2s^2S_{1/2}$-$2p^2P_{1/2}$ Lamb shift with an accuracy of order 0.1%, probably better than any Lamb shift measurement in a hydrogenic ion with $Z>3$.

Preliminary measurements of the yields of recoil ions under various experimental conditions are being pursued in the U.K. at Oxford and at the NSF, Daresbury, and in France at GANIL.

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X-RAY SPECTROSCOPY OF HIGHLY IONIZED ATOMS OF Ti THROUGH Zn IN A DENSE PLASMA

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Extensive studies have been carried out using a high-resolution curved crystal spectrometer on the structures of x-ray spectra from highly ionized atoms of first transition elements in a dense plasma produced by a vacuum spark.

K x-ray spectra from partially M-shell-ionized ions have been observed to investigate the structures of the ions in many electron system and the transition energies were determined.[1] Some Fe Kα lines are shifted to the long-wavelength side of the singly ionized characteristic lines of $FeK\alpha_{1,2}$. Systematic observations of Kβ lines from the M-shell-ionized ions for nuclear charge Z show that the square root of the transition frequency can be expressed as a linear function of Z for an isoelectronic sequence.

H-, He- and Li-like x-ray lines for Fe have been observed.[2] The transition wavelengths of He-like resonance series lines up to $1s6p$-$1s^2$ were determined. The experimental values approach to ones by Mewe's empirical formula[3] for transitions from highly excited levels such as 6p state. A highly resolved Kα spectrum is obtained and the structures of He-like and Li-like satellites are studied in detail.

He-like resonance lines of Ti through Zn have been measured and the transition wavelengths were first determined under careful experimental procedures.[4] The results are compared with theoretical predictions and are in good agreement with that by Safronova.[5] The theoretical values, however, include some uncertainties in relativistic and QED corrections of the He-like resonance line. Much theoretical works are needed for comparison with these experimental data.

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MEASUREMENT OF THE $^{19}F^{7+}$ 1s2p $^3P_1$-$^3P_2$ FINESTRUCTURE USING A FAST BEAM LASER RESONANCE TECHNIQUE

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The three $^3P_{1,F}$-$^3P_{2,F'}$ hyperfine components of the 1s2p $^3P_1$-$^3P_2$ finestructure interval in the helium-like ion F^{7+} have been measured using a fast ion beam laser resonance technique. The method involved inducing the three M1 transitions in a foil stripped fluorine ion beam using a high power c.w. CO_2 laser. The results are: 961.758(21) cm^{-1}, 953.606(22) cm^{-1} and 941.177(29) cm^{-1} for the 3/2-5/2, 1/2-3/2 and 3/2-3/2 components respectively.

Good agreement is obtained with a theoretical calculation of the HFS, and using this calculation, the FS interval is deduced from the above results to be 957.883(19) cm^{-1}. An improved theoretical calculation of the finestructure yields 957.87 cm^{-1}, and there is now good agreement between theory and experiment.

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RELATIVISTIC MODEL OF HIGHLY IONIZED ATOM PRESERVING NON-RELATIVISTIC STRUCTURE OF ELECTRONIC SHELLS

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Relativistic effects are of great importance while studying the spectra of multiply charged ions. In relativistic approach, the wave functions of jj coupling are usually chosen as the basis set. Then the non-relativistic shell nl^N splits into subshells $nlj_1^{N_1} nlj_2^{N_2}$ $(N=N_1+N_2,\ j_1=l-1/2,\ j_2=l+1/2)$ and the wave function of a system under consideration is obtained making use of the vectorial coupling of the angular momenta of separate subshells. However, usually even for comparatively high ionization degrees the LS coupling is the best inside a shell, therefore there is a need of a method, which could both account for relativistic effects as exact as possible and preserve non-relativistic electronic structure of a system.

Let us notice that for two subshells with the same nl we have the operators of total angular $\vec{J}=\vec{J}(j_1)+\vec{J}(j_2)$ and total quasispin $\vec{Q}=\vec{Q}(j_1)+\vec{Q}(j_2)$ momenta. However, we can put into operation the operator, which irreducible components in the second quantization formalism [1] are $A_\rho^{(1)} \sim [\alpha^{(qj_1)} \times \alpha^{(qj_2)}]^{(01)}_{0\rho}$. The commutation conditions for the components of the operators $\vec{A}, \vec{J}$ show that these operators are the generators of the group O_4. For classification of the irreducible representations of this group, two commuting operators of the angular momentum type $\vec{L}=\vec{J}\mp\vec{A}$ and $\vec{S}=\vec{J}\pm\vec{A}$ may be used. In non-relativistic limit they turn into usual orbital and spin angular momenta. Therefore the basis presented has considerable advantages in comparison with the one of jj coupling while identifying and classifying the spectra of ions in a wide range of ionization degrees.

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BRANCHING RATIOS AND OSCILLATOR STRENGTHS OF $\Delta n = 0$ TRANSITIONS IN THE L-SHELL OF C I, N I AND O I LIKE HEAVY IONS

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Wavefunctions for atomic structure calculations are at the best tested by experimental transitions probabilities. These can be derived from branching ratio- and lifetime measurements. Moreover experimental branching ratios are of great interest for in situ intensity calibration procedures in the spectral range of the EUV and VUV.[1,2]

Beam-foil and beam-gas excitation using the tandem accelerator at Bochum and the 1 MeV van de Graaff generator at Giessen have been employed to produce $2s^m 2p^n$-configurations (m = 0,1; n = 3,4,5) of O, F, Ne, and Si. Various $\Delta n = 0$ transitions have been observed using a 2.2 m grazing- and a 1 m normal-incidence monochromator with known detection efficiency at Bochum and Giessen, respectively.

Branching ratios and oscillator strengths -in connection with known experimental lifetimes- have been derived and are compared to theoretical predictions. The experimental results are a valuable test for the consideration of electron correlations in the theoretical calculations especially at the low Z-end of isoelectronic series. We find a good overall agreement with the data given from the non-closed-shell-many-electron theory (NCMET).[3]

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INTENSE X-RAY EMISSION IN THE INTERACTION OF LASERS WITH A SOLID SURFACE

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When the burst of hot laser plasma reaches a solid surface there is intense X-ray emission, specifically the lines of the principal series of hydrogen-like and helium-like ions are several times more intense than the emission in the same lines in the hot core of a laser-irradiated target plasma. The observed effect demonstrates a new way to produce intense X-ray emission through the interaction of a laser plasma with a solid surface.

X-RAY DIAGNOSTIC OF HOT AND DENSE PLASMA IN LOW-INDUCTANCE VACUUM SPARK

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X-ray spectroscopical diagnostic is used for study of hot and dense plasma micropinch (MP) in low-inductance vacuum spark (LIVS). Parameters of the LIVS are: W=1kJ, I_m=0.2MA, T/4=1.2 μs. Two methods of initiation are used: trigger spark and evaporation of anode material by a Nd-laser pulse ($\tau \simeq 1\mu s$, $E \simeq 100J$).

The electron temperature T_e for MP-plasmas of different electrode materials from Mg to Cu was estimated from relative intensities of lines of He-like ions and their satellites. It was shown that $T_e \simeq 4.5(Z_n-5)^2$eV.Effect of intensity redistribution of dielectronic satellites gives the value of the electron density of MP-plasma $n_e \simeq 10^{23}cm^{-3}$ for the elements Ca and Ti/1/.

It was obtained that the electron temperature of MP plasma in the case of equicomponent Fe+Mo alloy anodes increased up to 2.3keV compared with 1.3keV for pure Fe-anode.For (Ti+Mo)plasma T_e increased by the factor of 1.5.

Lower bounds of the parameter $n_e\tau \sim 10^{12}cm^{-3}s$ was derived from relative intensities of inner-shell excited and dielectronic satellites (T_z and T_e).

The observed line broadening $\Delta\lambda/\lambda \simeq (1.3...1.5)10^{-3}$ is considerably higher than possible Stark and Doppler thermal broadening.It seems connected with radial motions of emitting plasma with $v \simeq (2...3)10^7$cm/s.

In experiments with controlled evaporation of anode material in the discharge gap (laser initiation) the deep compression only occured in the case of sufficient linear density of plasma.

The results presented in this work are in a good agreement with predictions of the "radiative collapse" model/ 2 /.

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RELATIVISTIC ENERGY CONTRIBUTIONS TO THE N=2 TRIPLET LEVELS IN HELIUM-LIKE IONS

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The $1s2s\,^3S$ - $1s2p\,^3P_J$ (J = 0, 1, 2) transitions in helium-like ions can be used to test QED, but only if the other contributions to the transition energy, and especially the relativistic contributions, are known to high accuracy.

This work tests the relativistic calculations by comparing the theoretical ^3P_J splittings [1,2] (which are nearly independent of QED) with each other and with experiment. An estimate of the largest uncalculated relativistic term, of relative order α^4Z^4, is also made.

It is found that the MCDF-EAL method of Hata and Grant[1] gives poor results, and that the small discrepancy between Drake[2] and experiment[3] vanishes if the α^4Z^4 relativistic term is included.

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MEASUREMENTS OF THE 1s LAMBSHIFT IN HYDROGENLIKE Cl

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A quantity of fundamental interest in atomic spectroscopy is the 1s Lambshift in heavy hydrogen-like ions. We determined its value for chlorine with two different precision measurements of the 2p-1s transition energy. To obtain the appropriate accuracy we used a high resolution Bragg crystal spectrometer which was calibrated with the singly ionized Ar Kα lines. The Ar Kα lines are only a few eV below the Cl Lyα lines and its x-ray energy were determined to high accuracy (3ppm) by measuring the Bragg angle with a double flat crystal spectrometer. In order to cope with the rather small yields of excited hydrogen-like ions we used in the Cl experiment a position sensitive detector which avoids time consuming angular scans with the spectrometer. The two different experiments used different methods to produce the needed ion states. In the first measurement the ions were created when beams of fast Cl ions transversed a carbon foil which was monitored with the high resolution x-ray spectrometer.[1] Variation of the ion velocity enabled us to determine the Doppler shift and to test other effects like satellite shifts, stability etc. This procedure also yields a reliable error estimate. In the second experiment the chlorine Ly α lines were observed in a tokamak plasma device where the chlorine is predominatly ionized through multiple electron collisions.[2]

This method reduces significantly satellite shifts and Doppler shifts since the isotropic low ion velocity distribution yields a Doppler broadening of the line but no shift of its mean.

A detailed analysis of the results and an error analysis of the present and prospective experiments will be presented.

The present values are 0.87±0.10 eV for the beam foil experiment and 0.85±0.10 eV for the plasma experiment. Both results are in agreement with the theoretical value of 0.9384±0.0006 eV.[3]

This work was supported by the Department of Energy, Division of Chemical Science.

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A SYSTEMIZATION OF X-RAYS AND ELECTRON BINDING ENRGIES IN FREE HIGHLY CHARGED IONS

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Recently, the interest of atomic structure data and X-ray data of highly charged ions has increased, but the major atomic data sets are rather incomplete with respect to highly ionised heavy atoms and subsequent, compilations for highly ionised spezies are needed.

To obtain the most feasible information about the influence of outer-shell vacancies to atomic properties, single-configuration Dirac-Fock-Slater calculations in the frozen core approximation are carried out for all elements with $Z \leq 92$.

A summary about the expected X-ray energy shifts of the K_{α_1}-, K_{β_1}-, L_{α_1}- and the M_{α_1}-lines for highly charged ions is discussed. At ionization stages, corresponding to full subshells, characteristic changes in the gradient of the energy shifts appears. The occurence of outer-shell vacancies leads to typical periods in the X-ray energy shifts. At some electronic configurations the tendency of the satellite energy shifts changes from shifts to the high-energy side of the diagram lines to the low-energy side.

A systematical overview about the changes in the electron binding energies as a function of the ionization stage of the ionic ground state is given for the 1s1/2-, 2p3/2- and the 3d5/2-orbitals for all elements with $Z \leq 92$. Remarkable changes in the binding energy shifts appears for electronic noble gas configurations or for closures of d- and f-subshells. The ionization of a constant number of electrons from atoms with different atomic numbers leads to binding energy shifts, which are for the complete Z-region in the same order of magnitude.

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TRANSFER IONIZATION AND TWO-ELECTRON CAPTURE PROCESSES IN N^{6+}-He COLLISIONS AT 3-34 keV ENERGIES

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Energy gain spectroscopy is used to investigate the various electron capture channels in N^{6+} He collisions. It is found that, in addition to the dominant one electron capture into the N^{5+} (n=3) states, the two electron processes and especially transfer ionization have a large contribution to the production of N^{5+} ions for the highest energies investigated here.

The various channel for the reaction are :

(i) $A^{q+} + He \rightarrow A^{(q-1)*+} + He^{+}$
(ii) $A^{q+} + He \rightarrow A^{(q-2)*+} + He^{++}$
(iii) $A^{q+} + He \rightarrow A^{(q-2)*+} + He^{++} \rightarrow A^{(q-1)+} + He^{++} + e^{-}$
(iv) $A^{q+} + He \rightarrow A^{(q-1)*+} + He^{*+}$
(v) $A^{q+} + He \rightarrow A^{(q-1)*+} + He^{++} + e^{-}$

where (v) can be considered as a common Rydberg limit of (ii), (iii), (iv)

The ions produced by the E.C.R. source Micromafios (at Grenoble) are mass and energy selected before collision, the emerging beam is charge and energy analysed in a parallel plate electrostatic condensor. Exept for the (ii) channel the final charge state of the projectile is $(q-1)^{+}$ so it is possible to observe the relative intensity of the various channels in a single energy gain spectrum. It has been found that in N^{6+}-He collision the transfer ionisation (v) is the dominant two-electron processe and the importance of these processes (iii,iv,v) increases strongly with the colliding energy and the scattering angle, suggesting a mechanism involving smaller impact parameters.

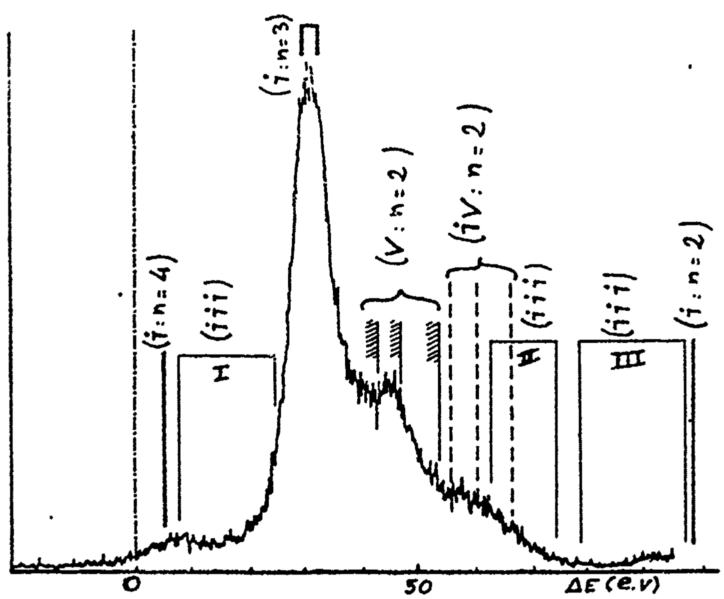

Fig. 1. Energy gain spectrum at 12 keV collision energy, the various channel are indicated. The autoionising double capture series shown (I,II,III) are those observed by electron spectroscopy (at 60 keV energy) (1).

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PREDICTION OF IMPURITY SPECTRAL EMISSION IN PLASMAS

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This paper summarises the development of a set of general purpose theoretical procedures for the prediction of spectral emission from plasmas, with emphasis on fusion plasmas. The first stage [1] was concerned with the calculation of populations of low levels of impurity ions in a statistical balance approximation in thermal plasmas of arbitrary electron and proton temperatures and densities. This was merged with associated calculations of ionisation stage abundances in equilibrium, time dependent and spatially inhomogeneous conditions to yield spectrum line emissivities of direct relevance for comparative and diagnostic studies of observed spectra. The integrated computer program package draws upon sets of basic atomic data. In the present work, the compilation of this basic data is addressed.

A set of computer programs has been developed and used to convert systematically atomic rate data, drawn from the literature, to standard forms and parameter ranges. Regularities in this data along isoelectronic sequences are exploited to infer rates for an arbitrary ion from a set of representative data (termed the 'general Z' database). From this, the input for the spectral prediction codes above is generated.

Presently data in the H, He, Li and Be isoelectronic sequences is prepared. The operation of the procedures which use interactive and graphical techniques is described and some cases studied.

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THE POPULATIONS OF EXCITED LEVELS OF HYDROGEN-LIKE AND HELIUM-LIKE IONS IN PLASMAS TRAVERSED BY NEUTRAL HYDROGEN BEAMS

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This paper examines the populations of excited levels of impurity ions in a spatially homogeneous plasma containing primarily thermal electrons and protons and monoenergetic neutral hydrogen atoms. Of special concern is the role of recombination which may include the radiative, three-body and di-electronic processes together with charge exchange capture from neutral hydrogen beams.

The influence of these primary processes on the populations is modified by radiative transitions and redistributive transitions due to collisions with electrons and protons in the plasma. The behaviour of the populations of the ions C^{+5}, C^{+4}, Ar^{+17} and Ar^{+16} with variation of plasma parameters is explored in the present work. A bundled principal quantum level picture and a more elaborate LS resolved picture are used which allow investigation of the expected spectral emission and its sensitivity to uncertainty in the primary rates.

The variation of the impurity ion spectrum in transiently recombining or ionising conditions is also considered.

UV SPECTROSCOPY OF CHARGE EXCHANGE COLLISION OF MULTICHARGED NITROGEN IONS (7+, 5+) WITH H_2 AND He

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We have observed the spectra obtained during the charge exchange collision of N^{7+}, $^{5+}$ with helium and molecular hydrogen with a grazing incidence spectrometer in the 10 - 130 nm spectral region. Multicharged ions are produced by the ECR source of the CEN in Grenoble.

Results obtained with N^{7+} concern the 4-3, 4-2 and 3-2 transitions of N VII.

With N^{5+} the relative excitation cross sections of the N V levels have been measured (within a 20% error bar) :

$$\text{He}: \quad \sigma 3p / \sigma 3s = 0.50 \qquad \sigma 3d / \sigma 3s = 0.5$$

$$H_2: \quad \sigma 4f / \sigma 4s = 2.9 \qquad \sigma 4d / \sigma 4s = 1.9$$

$$\sigma 3d / \sigma 4s = 10.6 \qquad \sigma 3p / \sigma 4s = 12.4 \qquad \sigma 3s / \sigma 4s = 4.5$$

The absolute values will be discussed.

The double electron capture has also been observed via the $2s2p\,^1P - 2s^2\,^1S$ N IV transition with an helium target. This phenomenum also exists with hydrogen but is blended with double collision.

TRANSITIONS IN FEW ELECTRON SPECTRA OF COPPER

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We report on spectra observed by beam-foil spectroscopy of a 10 MeV/aum ^{63}Cu ion beam from the UNILAC of GSI at Darmstadt. Ions emerging from a 180 $\mu g/cm^2$ carbon foil are mainly two and three electron ions. The ultra violet spectra were analysed by means of a Roman-Vodar 3 meter vacuum monochromator equiped with an aluminium coated ruled grating blazed for 250 Å. The observation was at 90° to the ion beam. The detector was a channeltron.

Many lines were observed and identified from 100 Å to 460 Å in 1^{st}, 2^{nd}, 3^{rd} and 4^{th} orders. The width at half maximum of peaks was about 1.4 Å. The main features are hydrogenic lines between levels 5-6, 6-7, 7-8, 8-9 in Cu XXVI, XXVII, XXVIII, the very strong resonance doublet components $1s^2 2s\,^2S - 1s^2 2p\,^2P_{1/2,\,3/2}$ of lithium-like Cu XXVII and the beryllium-like Cu XXVI transitions between low-lying levels $2s^2$, 2s 2p and $2p^2$.

We dedicated much attention to the $2s\,^3S_1 - 2p\,^3P_2$ line wich we measured in 1^{st} and 2^{nd} orders. The main uncertainty in absolute wavelengths is due to the error in apparent wavelengths of reference lines. Lifetime of the $2p\,^3P_2$ level was measured. Comparaisons with theory are developped.

SOLAR FLARE SPECTRA FROM THE HIGHLY IONISED IRON IONS

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During solar flares, the plasma temperature exceeds 10^7K. Spectral lines from the highly ionised iron ions are produced in the UV(~1000Å), XUV(~100Å) and X-ray(~ 10Å) wavelength regions. Atomic data have now been calculated for many of these ions using a computer package developed at University College London. Exemples are given of the diagnostic potential of these spectral lines with reference to analyses of satellite data (OSO-5[1], SMM-UVSP[2], SMM-XRP[3]).

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AUGER ELECTRON SPECTRA IN 5.5 MeV/amu Ne^{Q+} AND Ar^{Q+} ION IMPACT ON Ne

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A study of Ne K Auger spectra induced by 5.5 MeV/amu Ne^{3+}, Ne^{10+}, Ar^{6+} and Ar^{17+} heavy ions on Ne is presented. Some average quantities (the centroid energy of KLL Auger spectra, the average number of L vacancies produced simultaneously with the K vacancy, the effective charge of the projectile in the actual process, the satellite to total intensity ratio) characterising the KL^{n} ionization process have been extracted from these spectra. Relative K-shell ionization cross sections and KLM to KLL cross section ratios have been evaluated. The reduced experimental Z_{eff} values have been compared with the results of PWBA and BEA calculations. A simple model calculation is made in an attempt to interpret the variation of the probability for the ejection of an L-shell electron $/P_L/$ as a function of Z_{eff}/v_p. Some statements regarding individual lines and groups in the Auger spectra are made.